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Review article

Bioethanol and biodiesel blended fuels — Feasibility analysis of biofuel feedstocks in Bangladesh

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ABSTRACT

In 2019–2020, Bangladesh imported 5.2 million metric tonnes of petroleum products, worth 2.5 billion USD, and 50% of the imports were consumed by the transportation sector. Having limited natural oil reserves and being heavily dependent on oil imports, the country is vulnerable to shocks in the international oil market, which can jeopardize its consistent economic growth. The Government announced a 5% blending of bioethanol with gasoline in 2017, with broken rice, maize, and molasses as the feedstocks, but sourcing biofuel from food crops can hamper the country's food security. This study explores second and third generation feedstocks e.g., organic plants, seeds, agricultural residues, and waste animal fat or skin that can be collected and processed for the extraction of biofuels. Technical potential of biofuel from the feedstocks is analysed which shows that Bangladesh has a potential to extract 44.4 million metric tonnes of bioethanol in a year from agricultural residues with rice residue having the highest potential (71%). Ground nut and rubber seeds can be major feedstocks for biodiesel production having a potential of 61,000 and 42,000 metric tonnes per year, respectively. Waste chicken skin can be another promising feedstock for the extraction of biodiesel. Biofuels extracted from these non-edible feedstocks and blended with existing transport fuels can lessen Bangladesh's import bills through a sustainable, environmentally friendly manner.

Contents

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List of abbreviations

ASTM	American Society for Testing and Materials
BPC	Bangladesh Petroleum Corporation
BTU	British thermal unit
CO	Carbon monoxide
CO_2	Carbon dioxide
DAE	Department of Agricultural Extension
FAO	Food and Agriculture Organization
FR	Field residue
GDP	Gross domestic product
ha	Hectares
IEA	International Energy Agency
NO_x	Nitrogen oxides
PJ	Petajoules
PR	Process residue
SO_2	Sulphur dioxide

1. Introduction

Carbon dioxide (CO_2) is the biggest contributor to global warming among the greenhouse gases, with CO_2 emissions from anthropogenic activities having a share of almost 78% of all greenhouse gas emissions increase from 1970 to 2010 (Dong et al., 2019; Intergovernmental Panel on Climate Change, 2014). According to the International Energy Agency (IEA), global emissions of CO_2 reached around 33 gigatonnes in 2019 (Anon, 2020e), moreover, the transportation sector was responsible for more than a quarter of the total emissions (Adams et al., 2020; Anon, 2020). To mitigate the effects of global warming, it is essential to reduce CO_2 emissions from the burning of fuels in automobile engines and shift to alternative and cleaner fuels. The need for alternative fuels is more pronounced when the remaining global stock of fossil fuels such as crude oil and natural gas are looked at. The present reserves of crude oil are predicted to last till 2052 based on annual consumption rates of 4 billion tonnes (Ashraful et al., 2014).

Biofuels are a promising energy resource that can reduce the demands of crude oil and gasoline, and furthermore, decrease CO_2 emissions from vehicles (Naik et al., 2010). Automobile engines can burn gasoline blended with 5%–10% bioethanol with little or no modifications (Morales et al., 2015). Biodiesel with lower blends of 2% and 5% in diesel fuel has been found to run successfully in both existing and newer diesel engines without modification and even blends with up to 20% biodiesel can be used (Ogunkunle and Ahmed, 2019). Bioethanol and biodiesel are the two most popular biofuels that are being used as substitutes for regular gasoline and diesel (Clerici and Alimonti, 2015). As of 2019, USA and Brazil produce close to 62% of global biofuel with 697,000 barrels of oil equivalent and 444,000 barrels of oil equivalent, respectively (BP, 2020). The USA primarily produces bioethanol from corn (starch-based) while Brazil mainly relies on sugarcane (sugar-based) (Mohanty and Swain, 2019). Global biodiesel production stood at 699,000 barrels of oil equivalent in 2019 and is predicted to reach 41.4 billion litres by 2025 (BP, 2020; Rouhany and Montgomery, 2019). Among Asian countries, Indonesia, Malaysia, and Thailand produced the highest amounts of biodiesel with palm oil being the leading feedstock (Syafiuddin et al., 2020). Besides being a renewable resource with lower greenhouse gas emissions, biofuels are also cleaner in the sense that they produce less particulate matter after burning (Rouhany and Montgomery, 2019).

Generally, biofuels are classified into three or four generations, based on the source of raw materials (Syafiuddin et al., 2020; Susmozas et al., 2020; Singh et al., 2020a; Rodionova et al., 2017). First generation (1G) biofuels are extracted from edible feedstocks. Second generation (2G) biofuels are produced from non-edible feedstocks, and agricultural residue, the latter being obtained from edible feedstocks. Agricultural residues can be rice straw, rice husk, sugarcane bagasse, etc. Third generation (3G) ones involve sources that do not compete for land, such as microalgae, waste animal fat, and waste cooking oil. Fourth generation (4G) biofuels consist of solar fuels and electro-fuels. Bioethanol can be produced from sugar-based materials such as sugarcane, beet, molasses, starch-based feedstock like corn, wheat, potato, and cellulosic-based feedstock such as rice straw, bagasse (Naik et al., 2010; Rodionova et al., 2017). The steps for producing bioethanol typically involve extracting the sugar from the raw materials, fermenting the sugar into bioethanol, and then running a distillation process to purify the bioethanol (Najafi et al., 2009).

Biodiesel can generally be obtained from both edible and non-edible oils such as corn, palm, soybean, sunflower, castor and also animal fats and chicken skin, and waste cooking oil (Naik et al., 2010; Rodionova et al., 2017; Barua et al., 2020; Hussain et al., 2016). Microemulsion, thermal cracking, and transesterification are the commonly used processes for producing biodiesel (Ma and Hanna, 1999). Sujata and Kaushal (2020) investigated the supply chain of producing bioethanol from molasses in India and found that only 3% of automobile fuel could be blended which was far from the national target of 20% with the major reasons for the discrepancy being a lack of distillation capacity and a lack of diversity in raw material sources. Since, molasses, the primary raw material for bioethanol production in India, was found to be inadequate for achieving national blending targets, Jahnavi et al. (2017) reviewed the availability of various agricultural residues as a potential feedstock for bioethanol production. Rice husk, a residue generated in the rice milling industry, was estimated to have a global potential of producing 20.9 to 24.3 gigalitres of bioethanol annually (Abbas and Ansumali, 2010). Kim and Dale (2004) considered Asia to be the region with the highest bioethanol production capacity from sugarcane waste, having a potential of producing 41% of the global biofuel. Asia was also found to have the greatest potential in producing bioethanol from rice residues. In Iran, agricultural wastes can be utilized to generate 4.91 gigalitres of bioethanol with wheat, rice, barley, corn and sugarcane bagasse being the most suitable sources (Najafi et al., 2009). Work of Arapoglou et al. (2010) involved extracting ethanol from potato peel waste, which is a waste product from the potato processing industry and has a high starch content.

However, Hussain et al. (2016) explored the feasibility of biodiesel extracted from waste cooking oil in UAE and discussed that a large scale production scenario would be the most economical, and found a vehicle running on biodiesel having 23.1% less CO_2 emissions when compared to petroleum-derived diesel. On the other hand, Lozada et al. (2010) investigated the feasibility of biodiesel from palm oil in the Mexican transportation sector. They evaluated two scenarios, one based on regular diesel and the other used 5% and 10% biodiesel blending with diesel, over a period of 26 years. Achieving the blend targets will result in CO_2 emissions reductions of 148 million tonnes. In Thailand, rubber seed oil, a non-edible feedstock, was found to have promising results for producing biodiesel, with yields over 97% obtained via transesterification and the biofuel having properties within recommended standards (Roschat et al., 2017). Since a multitude of raw materials for the production of biofuels are available, it is recommended to diversify the feedstock in accordance with the sources available at each geographical location (Atabani et al., 2013; Gui et al., 2008). In a review article comparing the feasibility of edible oil, non-edible oil, and waste edible oil as potential feedstocks for biodiesel, it was suggested that making waste edible oil as the primary source of biodiesel, over the other two, would be the most beneficial due to its abundant nature with the added perk of mitigating its disposal issues (Gui et al., 2008). Edible and non-edible oils would be used in case of a fall in supply of the waste oil and moreover, this would also reduce competition of edible oils such as palm oil being a food or a fuel resource.

The advantages of biofuels are their renewability, cleanliness, ability to offset fossil fuel supply problems, develop a country's energy security, and lower greenhouse gas emissions (Ji and Long, 2016; Correa et al., 2019). Despite its renewable potential, the development of biofuels has certain negative implications that can offset the positive effects. 1G biofuels directly compete with agricultural lands and drive up food prices (Correa et al., 2019; Thompson, 2012). The demand for land also drives deforestation, the cutting of forests releasing large amounts of sequestered carbon dioxide into the atmosphere and causing a loss in native species (Elshout et al., 2019; Fargione et al., 2008). In this regard, 2G biofuels sourced from agricultural residue have an advantage as it does not require new land areas for crop growth, and the waste portions of the original food crop can be utilized for fuel extraction. While 2G biofuels, alongside other generations, are considered clean, the production phases are not free of greenhouse gas emissions (Ji and Long, 2016). The stages of plant cultivation, use of fertilizers, extraction of residue, transport, and residue treatment process all release greenhouse gases. Although biofuels have advantages that serve to combat climate change, they are also not immune from the risks of climate change. Stromberg et al. (2011) assessed wind damage on biofuel feedstocks for the Philippines, a country with frequent exposures to typhoons. They found feedstock yields dropping as a direct result of the increased wind damage, and the vulnerability to climate change depends on feedstock planted and location choice. Jaime et al. (2018) forecasted that Europe will lose thousands of hectares of land of rapeseed cultivation as a result of climate change. However, white mustard, another potential biofuel feedstock, could replace rapeseed as the land will become suitable for its cultivation.

Prospects of biomass from agricultural residues, forest residues, animal manure, and municipal solid waste in the context of Bangladesh have been explored in certain studies (Halder et al., 2014; Huda et al., 2014; Adnan et al., 2021). Miskat et al. (2020) reviewed the prospects of extracting bioethanol from agricultural residues of rice, wheat, corn, sugarcane, cotton, and jute in Bangladesh. The major crops produced about 65.36 million tonnes of residue from which 32 million tonnes of bioethanol could be generated. Barua et al. (2020) investigated biodiesel production from chicken fat in Bangladesh and estimated 2.45 million barrels of biodiesel could be extracted from the 3.35 million metric tonnes of chicken consumed in 2015–2016. The biodiesel production would also lead to a possible savings of 134 million USD in the country's oil imports. In an experimental study (Swaraz et al., 2019), a maximum of 0.323 g/g of bioethanol from palm sap and 0.232 g/g of bioethanol from fruit palm were obtained from a wild date palm growing region of Jhenaidah, Bangladesh. The study estimated 8076 L of bioethanol could be produced in the best-case scenario from one hectare of land consisting of 500 palm trees. Duckweed, an aquatic plant, is a second generation biofuel feedstock that can be fermented to produce biogas or bioethanol (Nahar and Sunny). Johnston and Holloway (2007) calculated that Bangladesh bore a potential of producing 31,217 L of biodiesel based on available feedstock data of 2003. Previous research in Bangladesh has greatly involved studying the potential of generating biogas from agricultural wastes and animal manure to use as cooking fuel and/or electricity production in rural households.

Bangladesh has limited natural reserves of crude oil, and as a result, has to solely depend on imports to meet its oil demand. Therefore, the aim of this paper is to study the potential of producing 2G biofuels, primarily from non-edible feedstock such as agricultural residues and non-edible crops, commercially grown in Bangladesh. Certain crops which are not commercially cultivated in the country but are suitable as biofuel feedstocks are also discussed. The focus is on biodiesel and bioethanol since they can be blended with diesel and gasoline available on the market. The focus on non-edible sources was chosen to avoid the food vs. fuel dilemma as depending directly on edible sources can harm the food security of the country. Thus, there exists a monetary savings potential in imports of fuel oil and reduce the country's dependence on the international fuel market. The quantitative potential of these biodiesel and bioethanol markets is explored which shall assist in determining the feasibility of biofuels in the country. The possible socioeconomic impact and environmental impact of developing a biofuel culture is discussed following with the recommendations to biofuel diffusion. Although the government announced the approval of biofuel blended gasoline, the project has not taken off and a clear roadmap covering the whole supply chain does not yet exist. In that regard, the results of this study can be of interest not only to other researchers but also to the stakeholders and the authority in charge of expanding the country's biofuel capacities.

2. Overview of energy status in bangladesh

Natural gas is the most abundant energy resource of Bangladesh, with national reserves of 11.47 trillion cubic feet as of 2018 (Petrobangla, 2018). In contrast, nationwide coal and oil production amounted to 0.019 and 0.007 quadrillions BTU, respectively (Anon, 2020g). As of December 2020, Bangladesh had an installed capacity of 21,239 MW and generated over 51% of its electricity from burning natural gas followed by a combined 33% from furnace oil and high speed diesel (Anon, 2020a). As a result of a lack of natural reserves of oil, the country is heavily dependent on imports for its crude oil needs. In 2019–2020, 5.2 million tonnes of oil, crude and refined, were imported, as listed in Table 1, while the transportation sector consumed 50% of the total petroleum products available (Anon, 2021b, 2020d).

Table 1
Import of petroleum products in 2019–2020 in Bangladesh (Anon, 2021b, 2020d).

	Quantity (metric tonnes)	Value (USD million)
Crude oil	1,151,814	451
Furnace oil	175,693	81
HSD, Jet fuel, Refined oils	3,873,131	1,993
Total	5,200,908	2,525

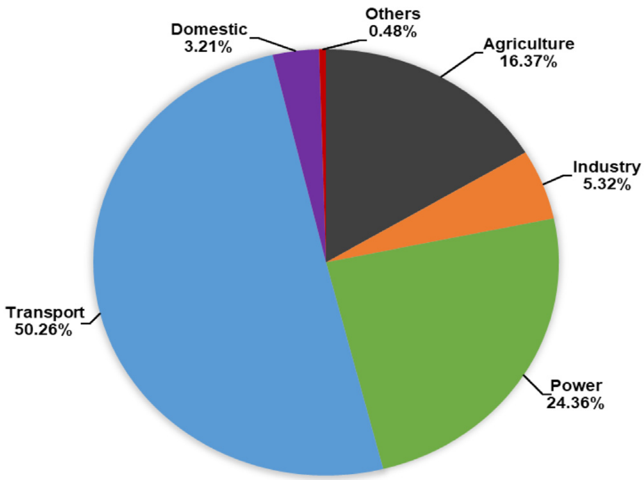

Fig. 1. Sector-wise consumption of petroleum products in Bangladesh (Anon, 2020d).

Fig. 1 illustrates the consumption of petroleum products, which include gasoline, diesel, jet fuel, and lubricating oil, by different sectors in Bangladesh. The demand for petroleum products is estimated to grow at rates of 2 to 4% and if this growth is sustained, Bangladesh will see oil demands of 15 million tonnes by 2030. According to BP Statistical Review, Bangladesh emitted a total of 106.5 million tonnes of CO_2 in 2019, which was 17.7% greater than the previous year (BP, 2020). The transportation sector released 12 million tonnes of CO_2 into the atmosphere, which was 14% of the total CO_2 emissions in the country (Anon, 2020c).

Bangladesh is experiencing a robust economic growth (World Bank, 2019) alongside an increase in population, however, meeting the rising energy demands from the scarce national oil resources within the limited land area is of significant concern. Biofuels can be a sustainable solution in this regard. Biofuels can also play an integral role in achieving the government's recent pledge to reduce greenhouse gas emissions in the transport and energy sectors by 5% (Anon, 2015). The utilization of biofuels can bring benefits in multiple avenues such as reduction of greenhouse gas emissions in the transportation sector, decreasing fossil fuel consumption and dependence, reducing spending on fossil fuel imports, boosting local energy security, and development of a sustainable fuel and energy resource.

In 2017, the Government of Bangladesh allowed the use of the E5 blended fuel, a mixture of 5% bioethanol with 95% gasoline, in automobiles with the bioethanol to be sourced from biomass (Anon, 2020f). Initial estimations cited annual bioethanol production of 18 million litres, which would either require 60,000 tonnes of broken rice or 62,000 tonnes of maize or 97,000 tonnes of molasses. However, the selection of raw materials, which act as food sources for humans and livestock, has raised concerns about harming the food security of the population. It is essential that crops for biofuels do not actively compete with edible crops in a country with a limited supply of agricultural land and thus, it would be prudent for Bangladesh to explore biofuel production from agricultural wastes and residues.

Close to 80% of the country's soil type is floodplain soils, while the remaining is made up of hill soils and terrace soils (Biswas and Naher, 2019). FAO classified the land area of Bangladesh into 30 different agroecological zones based on physiography, depth and duration of seasonal flooding, length of growing period, length of unreliable rainfall, length of winter, and frequency of high summer temperatures (UNDP, 1988). The soil type determines the types of crops planted and the cultivation practices (Nasim et al., 2018). As part of the Ganges delta, the land is enriched with fertile alluvial soil and rice is the majorly cultivated crop, occupying three-quarters of the country's crop coverage area (Huda et al., 2014). The wide adaptability of rice to the different agroecological zones of the country has made it the most suitable crop for cultivation (Nasim et al., 2018). The commonly available biomass resources in Bangladesh are agricultural crop residues, animal manure, wood wastes, and municipal solid waste (Huda et al., 2014). Rofiqul Islam et al. (2008) estimated that almost 46% of the total biomass energy in Bangladesh comes from agricultural residues of rice straw, rice husk, jute stick, and sugarcane bagasse. Agricultural residues commonly serve as fuel for cooking in rural kitchens, animal feed, and animal bedding (Halder et al., 2014). Traditionally, straws, husks, and baggage from different agricultural crops are used for domestic cooking while animal waste such as cow dung and chicken excreta act as fertilizers. Mondal and Denich (2010) reported about 50% of the generated rice husk is used in rural cooking. Halder et al. (2014) found that the total agricultural residues produced in Bangladesh in 2012–2013 had an energy potential of 582.33 PJ.

3. Methodology

A traditional literature review process has been adopted in this paper. Notably, traditional review encompasses a broader focus to information related to theories, research methods, and empirical results, and policies (Li and Wang, 2018; Rozas and Klein, 2010). In fact, such review covers major areas and serves the purpose of justifying further research in a subject area (Li and Wang, 2018). It provides an overview of the primary findings on the work done so far in a particular field that is quicker to grasp (Rozas and Klein, 2010).

This is an exploratory study with a quantitative approach. In the first step, a literature review aimed at identifying the different possible raw materials for bioethanol and biodiesel production was carried out. While doing this, we prioritized on the studies which were published in the last 10 years. The next step was to determine which of the potential biofuel feedstock grows naturally or being commercially cultivated in Bangladesh. For these two steps, the types of sources looked at were, firstly, existing scientific papers and case studies on raw materials of biofuel and crop growth and cultivation in Bangladesh, and secondly, the national crop production databases maintained by the Ministry of Agriculture, Bangladesh. Search terms such as 'biofuel sources', 'biofuel feedstock', 'biofuel raw materials', 'biofuel agricultural residue', 'biofuel feasibility', 'bioethanol', 'biodiesel', and 'biofuel Bangladesh' were used for the literature study. Databases of Scopus and Web of Science were used to search for relevant scientific articles. In the third step, the annual production amounts of the cultivated feedstock were obtained. Finally, based on the lignocellulosic biomass content or the oil content of the raw materials,

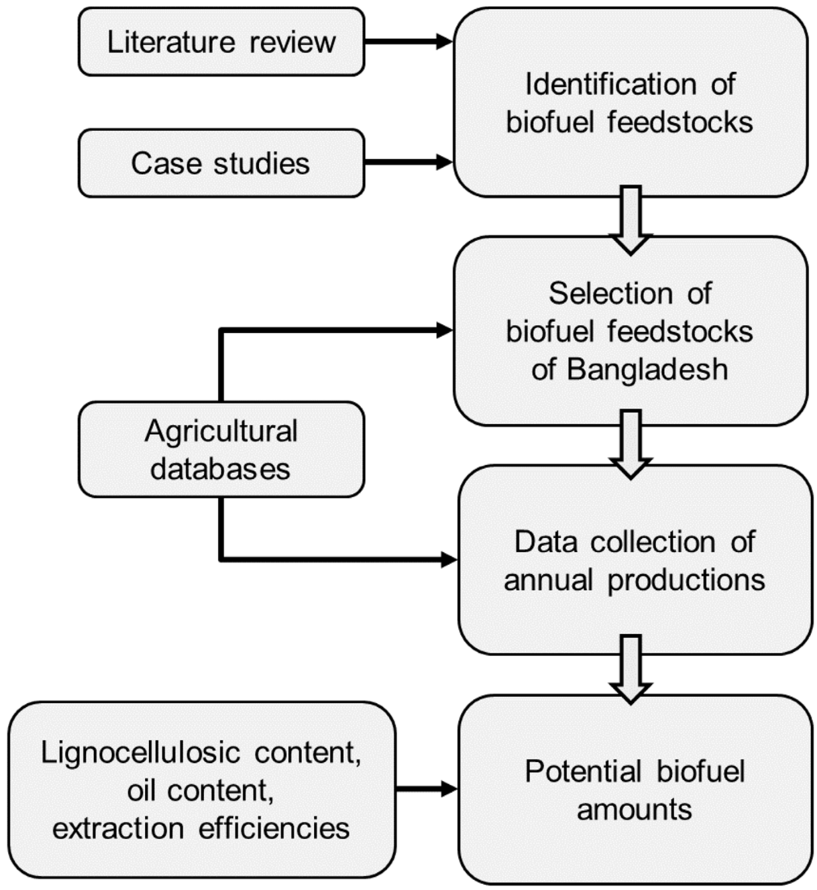

Fig. 2. Flow chart of the methodology.

estimates on the potential biofuel extraction amounts were made. A flow chart of the steps is illustrated in Fig. 2.

After an initial search, a total of 100 studies were selected encompassing scientific articles, conference proceedings, and book chapters relevant to the search terms. In the later stage, out of the 100 pieces of literature initially selected, 32 were related to a combination of the terms 'biomass', 'biogas', 'biofuel', and 'Bangladesh'. A screening process was carried out where studies involving first generation or edible biofuel feedstock, and articles that had 'biomass', 'biogas', and 'biofuel' only in keywords or references were excluded, after which the final number of selected literature was 71. With the biofuel feedstock identified, the goal of the next search step was to identify data sources on crop production in Bangladesh from various government published reports and databases. In this study, the national crop production data were collected from various sources including governmental reports (Department of Agricultural Extension, 2021; Anon, 2021a; Mahmud, 2019; Anon, 2021c,d,e; Bangladesh Bureau of Statistics, 2018). However, not all of the statistical reports were updated, with some including data on the fiscal year 2018–2019 as the latest.

In this study, the minimum oil content of a crop seed was considered to get a lower threshold of the biodiesel potential. Agricultural residues fall under two categories: field and process (Huda et al., 2014). Field residue (FR) is the waste collected directly from the cropland after harvest season and is widely utilized as a fertilizer. Process residue (PR) is the waste generated after the harvested crops are processed in the mills. For each crop, the amount of residue generated was calculated firstly, based on reported values of FR and PR (Halder et al., 2014). Since a 100% recovery factor of the agricultural residue is not realistic, collectable coefficients for different crop residues from literature were utilized and consequently, the potential bioethanol yield was evaluated. The collectable coefficient corresponds to the maximum amount of crop residue that can be gathered from the field and utilized (Fang et al., 2018).

4. Raw materials for biodiesel production

Biodiesel is generally obtained through a process known as transesterification where vegetable oils or animal fats chemically react with an alcohol, methanol is commonly used, in the presence of a catalyst (Van Gerpen, 2005). The products of this chemical reaction include fatty acid methyl esters which are recognized as biodiesel. Transesterification is recognized as the most favourable conversion technology as it yields biodiesel with properties close to regular diesel and also because of its suitability for large scale industrial production (Mofijur et al., 2016). The positive characteristics of biodiesel include biodegradability, non-explosiveness, non-flammability, and non-toxicity, alongside an added benefit of being renewable (Mofijur et al., 2016). Globally, there are over 350 oil-bearing crops that are perceived as raw materials for biodiesel and these feedstocks can be broadly divided into four generations (Syafiuddin et al., 2020; Singh et al., 2020a). First generation (1G) feedstock, also known as edible oil sources, includes palm oil, sunflower oil, coconut oil, soybean, rapeseed, rice bran, walnut, etc. Second generation (2G) sources consist of non-edible vegetable oils such as Jatropha, Jojoba, Karanja, Neem, Rubber etc. Although 2G biodiesel does not compete with edible stocks, the cultivation of the 2G feedstocks still requires large areas of land that could have been arable and planted with food crops (Gui et al., 2008). However, several studies have concluded that non-edible feedstocks, such as jatropha, karanja, rubber, can be grown on marginal lands and wastelands, thus, lowering competition with food supply (Singh et al., 2020a; Kumar and Sharma, 2011; Babazadeh, 2017; Ben Fradj et al., 2016). Microalgae, waste cooking oil, and animal fats, which include tallow, poultry fat, and fish, constitute the third generation (3G) feedstock. 3G feedstock possesses a significant advantage of having less impact on food supply but their large scale collection and production act as major obstacles (Singh et al., 2020a). Fourth generation (4G) biodiesel is a developing area of research and is obtained from electro-fuels and solar fuels, with their prime benefits being higher lipid and energy content, and a superior CO_2 absorbing capacity (Syafiuddin et al., 2020; Singh et al., 2020a; Moravvej et al., 2019).

4.1. Steps for 2G and 3G biodiesel production

The first and foremost step of extraction of biodiesel from non-edible vegetable oils (2G) starts with the separation of kernels or seeds. A simple blender or grater is used for this process and the product is later passed through a filter to extract the seeds. However, if the seeds do not open using this conventional method, they are cracked open manually. This alternative method is labour intensive and uses stomper and mallets (Islam et al., 2004; Sanford et al., 2009). These seeds are later dried in sunlight until the desired moisture content is reached, which is around 15% since it has the highest yield output (Sanford et al., 2009). This process normally takes around 3–5 days at a desired temperature of around 30–40 °C (Islam et al., 2004; Meher et al., 2006). The most common technique of oil extraction from these seeds are mechanical extraction, chemical extraction, and enzymatic extraction (Meher et al., 2006).

Once the oil is extracted it is treated to reduce viscous properties to make it more feasible for combustion. In the perspective of Bangladesh, the most widely used approach is transesterification. The processes can be slightly modified due to factors of production such as reaction time, catalyst type, and a mixture of the solvent. The oil is reacted with an alcohol (mostly methanol) at optimum temperature and pressure to produce fatty acids alkyl esters and by-products such as glycol (Al-Zuhair, 2007). Generally, the catalysts used are alkoxides, namely sodium hydroxide or sodium methoxide (Ruwwe, 2008). Once the reaction is over the methanol must be removed by a flash chamber at 50–75 °C and the removal stage takes roughly 2 h (Chitra et al., 2005). Multiple works of literature mention the usage of such a technique. For instance, Nabi et al. (2009a) discussed biodiesel production from karanja (Pongamia pinnata) in Bangladesh. Similarly, Nabi et al. (2009b) also showed the production of oil from cotton seeds. Morshed et al. (2011) reported about the potential of rubber seed.

In Bangladesh, the most prominent source of 3G biodiesel is chicken skin or waste chicken fat Barua et al. (2020). There are multiple techniques used to extract oil from such materials. These methods are melting, Soxhlet extraction, microwave heating, ultrasound-assisted, and supercritical carbon dioxide (Kirubakaran and Arul Mozhi Selvan, 2018). The extracted oil is further processed to produce usable fuel. The high viscosity of such fat makes the fuel undesirable for diesel engines. Therefore, the oil is either blended with other oils, micro-emulsified, pyrolysed, or transesterified (Kirubakaran and Arul Mozhi Selvan, 2018). The simplest method is transesterification since it requires fundamental infrastructure with a minimum amount of external reagents (Barua et al., 2020). This is a reversible reaction to favour the forward direction while the alcohol concentration should always be high. The catalyst can be chosen depending on the time availability and budget. Wei et al. (2009) proposed the usage of eggshells which are mainly composed of $CaCO_3$ due to their large availability. However, NaOH, fish bones can also be used as a catalyst (Yasin et al., 2017). Chowdhurya et al. successfully conducted an experiment in Bangladesh to achieve yields of around 35%. A schematic of the production steps is illustrated in Fig. 3.

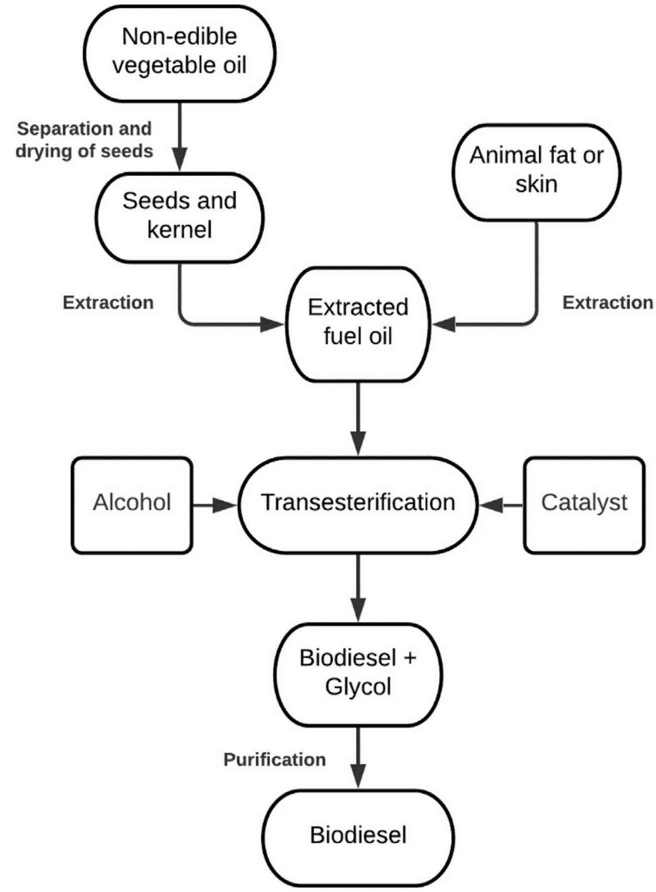

Fig. 3. Flow diagram for biodiesel production from non-edible vegetable oil (2G), and animal fats or skin (3G) (Singh et al., 2020a).

4.2. Rubber seed oil

According to FAO data of 2019, rubber plantations covered 226,935 hectares (ha) of land in Bangladesh with a rubber yield of 100.5 kg/ha (Anon, 2021e). The rubber seeds from the rubber trees are considered a waste product and has a maximum oil content of 49% (Morshed et al., 2011). One hectare of rubber plantation is found to produce 217 kg of rubber seed oil in a calendar year (Ramadhas et al., 2005). Based on the yield, annual rubber seed oil generation is about 0.05 million metric tonnes. Considering a conversion efficiency of 86% (Morshed et al., 2011), 0.04 million metric tonnes of biodiesel can be sourced from rubber seeds in Bangladesh per annum. Morshed et al. (2011) employed a three-step approach of saponification of the oil, acidification of the soap, and esterification of the free fatty acids, to extract biodiesel from rubber seed oil and concluded the biofuel has properties comparable with regular diesel. Calorific value, kinematic viscosity, flash point, cloud point and pour point of the extracted biodiesel were 32.6 MJ/kg, 4.5 mm^2/s (at 40 °C), 120 °C, 3 °C, and −5 °C, respectively.

4.3. Castor

Castor is a plant that can grow easily and almost anywhere, even in harsh soils, and is regarded as unwanted in Bangladesh. It is a non-edible source with its seeds having an oil content between 40%–55% (Keera et al., 2018; Deb et al., 2017). The plant has a long lifespan and bears a large number of seeds every year. Keera et al. (2018) achieved a 95% biodiesel yield from refined castor oil while certain properties such as pour point and cloud point were low enough to be suitable in diesel engines in colder months. FAO reported castor oil seeds grew over 364 ha in Bangladesh in 2019 and estimated annual production of 254 tonnes. Deb et al. (2017) collected castor seeds growing in Sylhet, Bangladesh, which gave a minimum oil content of 48.3%, and extracted biodiesel from the castor oil. The biodiesel from castor oil had a calorific value of 36.25 MJ/kg while the density and the kinematic viscosity were higher than conventional diesel. To mitigate the effects of a higher value of the kinematic viscosity, a biofuel blend of 70% biodiesel and 30% diesel was found to have successful results when used in a diesel engine. If the seed oil content of 48.3% and biodiesel yield of 95% is considered, the potential production of biodiesel from castor seed is calculated to be 116.54 tonnes.

4.4. Sunflower

Sunflowers were commercially cultivated over 2730 ha in 2019–2020 in Bangladesh and the DAE aims to double the cultivated area in the next fiscal year by encouraging more farmers to take up sunflower planting and distributing high quality seeds (Department of Agricultural Extension, 2021). The southern district of Barguna in Barisal division had the highest land coverage for sunflowers (Anon, 2020b). Annual production of the crop stood at 5720 tonnes and the extracted sunflower oil can be a source of edible oil or as a feedstock for biodiesel generation. On a unit hectare basis, sunflower seeds have a higher oil yield when compared to soybean and the crop requires less fertilizer and water than rapeseed (Singh et al., 2020a). With an oil yield of 35%, sunflower seeds can potentially produce 1907 tonnes of biodiesel at a conversion efficiency of 95.38% (Atabani et al., 2012). Dincer et al. (2015) found biodiesel extracted from sunflower oil had density and kinematic viscosity properties equivalent to the ASTM D6751 biodiesel standard while the flash point was higher, which can be an advantage as the high temperature lowers the risk of autoignition during storage or transport.

4.5. Linseed

Linseed is a herbaceous type crop and in 2019 was cultivated over 2300 ha of land in Bangladesh, yielding close to 2390 tonnes of the crop (Department of Agricultural Extension, 2021). Dhaka and Khulna divisions observe the most yield of linseed (Anon, 2020b). Habibullah et al. concluded linseed oil can be a valuable biodiesel crop for Bangladesh as the country has a suitable climate and soil condition (Habibullah et al., 2015). However, according to the Bangladesh Bureau of Statistics (Anon, 2020b), linseed cultivation is seeing a decreasing trend since 2017. It has a high oil content, between 40%–44%, a high proportion of unsaturated fats, and being a non-edible crop, it possesses the potential to be a biodiesel feedstock. Using potassium hydroxide as the catalyst, in situ transesterification of linseed oil with methanol as a solvent and tetrahydrofuran as a co-solvent gave a maximum biodiesel yield of 93.15% (Taherkhani and Sadrameli, 2017). The cultivated linseed can generate around 890 tonnes of biodiesel.

4.6. Ground nut

Ground nut or peanut, locally known as '*cheena badam*', is a legume crop that is grown in all divisions of Bangladesh and is mostly used in processed foods. In 2019–2020, it was grown over an area of 92,700 ha and the DAE recorded annual production stood at 169,900 tonnes (Department of Agricultural Extension, 2021). The cultivation of ground nut is heavily concentrated in the northwest division of Rangpur (Anon, 2020b). Seeds of the crop have a minimum oil content of 38%. The DAE has been carrying out activities to encourage more farmers to plant high yielding ground nut varieties and has set higher yield targets for the next fiscal years. A biodiesel extraction process based on diesel-based reverse-micellar microemulsions as the extraction solvent exhibited an efficiency of almost 95% at room temperature and within an extraction duration of 10 min Nguyen et al. (2010). Considering an optimistic scenario where all the harvested ground nut is utilized for biodiesel generation, a total of more than 61,000 tonnes of the biofuel can be generated. Moreover, the shell of the ground nut is an agricultural residue from which biodiesel can be produced after oil extraction (Duc et al., 2019). The shell also has high lignin content, therefore, making it a potential bioethanol feedstock as well.

4.7. Sesame seed

Sesame is a flowering plant with the sesame seed considered as an important oil crop. Locally known as '*teel*', the crop is grown all over Bangladesh with a greater concentration of the harvest centred in Khulna division. For 2019–2020, the DAE recorded 78,600 tonnes of sesame production from a total farmed land of over 68,400 ha (Department of Agricultural Extension, 2021). Sesame has an oil content of 37% which rises to 63% for some varieties. Saydut et al. (2008) achieved a maximum conversion of 74% of the oil into methyl esters via transesterification. When compared to regular biodiesel standards, the sesame biodiesel was found to have potential, but it has a higher viscosity, lower volatility, and lower calorific value, thereby limiting its use in automobile engines. The current harvest of sesame in the country can be used to obtain around 21,500 tonnes of biodiesel.

4.8. Chicken skin

Chicken skin is a potential 3G feedstock for obtaining biodiesel and is generally considered to be a waste in Bangladesh. The skin contains a higher proportion of fatty acids than the meat, has a methyl ester yield of 87.4%, and a lower heating value of 40 MJ/kg for the biodiesel extracted from the chicken skin Barua et al. (2020). The Ministry of Fisheries and Livestock reported 7.678 million metric tonnes of meat were supplied to the population in 2019–2020 (Anon, 2021d). Considering 54% of the total meat were consumption of chicken meat, and 1 kg of chicken meat gave 0.1 kg of skin, with a biodiesel yield of 95% and biodiesel density of 0.88 kg/litre, 4.15 million metric tonnes of chicken meat can result in almost 447 million litres of biodiesel in Bangladesh (Barua et al., 2020). However, the collection of chicken skin on a large and feasible scale is an issue and in Ref. Barua et al. (2020) it was recommended that the government conduct awareness programs to educate people on its value. Besides the skin, the feathers of the chicken are classified as a waste, and they can also be utilized for biodiesel production. Chicken feather has fat that can be extracted and then transesterified to remove the biodiesel (Chowdhury et al., 2021; Tesfaye et al., 2017). Purandaradas et al. experimented on chicken and rooster feathers and found the extracted biodiesel has properties within the ASTM 6751 standards (Purandaradas et al., 2018).

4.9. Other potential feedstocks

Alongside the cultivated crops in Bangladesh, studies have also been carried out involving non-native crops which possess high potentials to produce biodiesel. Jatropha curcas is a short tree or shrub species with non-edible vegetable oil seeds that is not commercially cultivated in Bangladesh. The oil from jatropha can be converted into methyl esters by the transesterification process. Prodhan et al. (2020) extracted biodiesel, with a 95% efficiency under optimal conditions, from the jatropha seeds that grew naturally in Bangladesh. Chakrabarty et al. (2019) planted 45 variants of Jatropha curcas at Gazipur, Bangladesh, and found substantial genetic diversity which if selectively utilized has the potential to enhance biofuel production in the country. Blended diesel having 5% jatropha-based biodiesel showed the closest engine performance to regular diesel. Apart from being used as liquid fuel, jatropha oil may also be used as a raw material for soaps (Chitra and Dhyani, 2006). According to the same literature, it could be used directly as engine oil in pumps and generators. Another biofuel feedstock, karanja, is obtained from the Pongamia pinnata tree, which has multiple non-edible products and can grow in almost all soil types. The karanja seed has an oil content ranging from 30% to 40% (Subnom et al., 2016). Nabi et al. (2009a) extracted biodiesel from karanja oil at a maximum yield of about 97% and suggested the planting of karanja on the country's unused lands.

4.10. Biodiesel potential

According to the production data, ground nut is found to have the highest potential for biodiesel in the country. However, ground nut is edible and acts as a raw material in the processed foods industry. The use of ground nut as a biofuel feedstock will create a new non-edible demand which directly competes with the edible market demand and drive up the price of the crop. Non-edible sources such as rubber seed and castor seed have the capacity to generate approximately 42,350 and 116 metric tonnes of biodiesel in Bangladesh, respectively. Other non-edible oil crops like *Jatropha curcas* and karanja, which possess high potential in biodiesel generation, are not as widely cultivated in Bangladesh as in other neighbouring countries. It is estimated that a total of 128,000 tonnes of biodiesel can be extracted from a mixture of 2G and 3G feedstock. Furthermore, in an optimistic scenario where all the waste chicken skin is collected, 447 million litres of biodiesel can be obtained from a 3G feedstock like chicken skin. The individual biodiesel potential of various raw materials is shown in Fig. 4.

5. Raw materials for bioethanol production

Bioethanol is produced from plant biomass and can be generally classified into three generations. First generation (1G) bioethanol is derived from sugarcane, corn, potato, sweet potato, cassava, barley, wheat, sorghum, sugar beet, and these crops are either starch-based or sugar-based (Ayodele et al., 2020). Since the 1G feedstock for fuel generation are food-grade crops, they are in direct competition with arable lands devoted for food and give rise to food vs fuel debates (Thompson, 2012). These conflicts led to the development of bioethanol extraction from agricultural residues which is composed of lignocellulosic biomass such as rice straw, rice husk, coconut husk, sugarcane bagasse, corn stover, wheat straw, and cotton stalk (Sharma et al., 2020). Bioethanol obtained from these non-food feedstocks is also known as second generation (2G). Lignocellulosic biomass mainly consists of lignin (15%–20%), cellulose (40%–50%), and hemicellulose (25%–35%) (Gray et al., 2006). Feedstock for third generation (3G) bioethanol comes from algal biomass, moreover, some strains of algae can also produce biodiesel (Sharma et al., 2020). Modification of algal strains through genetic engineering to enhance biofuel yields leads to another breed of feedstock that is termed as fourth generation (4G) but can also be considered as an augmentation of 3G biofuels (Sharma et al., 2020). All generations of biofuel carry an advantage of being environmentally friendly, however, 1G biofuels are limited as their feedstock has a primary function of being food crops. 2G, 3G, and 4G have the added advantage of not competing with food crops but the technologies to convert these feedstocks into biofuels often have higher costs.

Table 2 lists the annual production statistics of the fiscal year of 2019–2020 of the main crops cultivated in Bangladesh along with the various field and process residues generated from each crop (Department of Agricultural Extension, 2021). While annual production amounts, and consequently, biomass yield too, may differ, year-to-year due to the weather, the crop production of one fiscal year of 2019–2020 was chosen to determine the technical potential of biofuels. Rice exhibited the highest production and the crop left behind the straw in the field and the husk in the process mills. The straw or stalk was the field residue from the cultivation of corn, wheat, and jute, while sugarcane produced leaves as waste in the field and bagasse as process residue.

Values of FR and PR of various crops taken from literature and used in this work are presented in Table 3 (Halder et al., 2014; Huda et al., 2014). FR and PR values can vary depending on the local climate and soil type, and the values presented were obtained from crop statistics of Bangladesh and neighbouring Asian countries (Halder et al., 2014). The collectable coefficients of the various residue types are obtained from the work of Fang et al. (2018). The theoretical bioethanol conversion equals the maximum amount of bioethanol obtained from the glucose content (Morais et al., 2019).

5.1. Steps for 2G bioethanol production

A form of technology for converting lignocellulosic biomass into bioethanol is the biochemical route, which involves the steps of pre-treatment, hydrolysis, and fermentation (Soccol et al., 2011). The first step of pre-treatment comprises of separation of the lignocellulosic biomass to enhance the access of cellulose and hemicellulose to hydrolysis (Sharma et al., 2020). This separation of the cellulose components leads to an increased yield of fermentable sugars from cellulose and hemicellulose. Different methods of pre-treatment, such as physical and chemical means, exist. During hydrolysis, the long-chain carbohydrates are converted or broken down, a process also known as saccharification, into different monomers of sugar with the assistance of either acid catalysts or enzyme catalysts (Sharma et al., 2020). The converted sugar monomers are then acted upon by microorganisms, yeast, and bacteria are commonly used, and by the process of fermentation transformed into ethanol and other byproducts (Sharma et al., 2020; Toor et al., 2020). Finally, the ethanol mixture passes through distillation processes in a refinery to produce purer blends of bioethanol.

5.2. Rice

Rice is the most cultivated crop in Bangladesh, being the staple food of more than 150 million people, taking up about 76% of agricultural land, and between 2019–2020, total rice production was reported to be about 38.7 million metric tonnes (Huda et al., 2014; Department of Agricultural Extension, 2021; Mottaleb and Mishra, 2016). A statistical yearbook for 2019 published by the

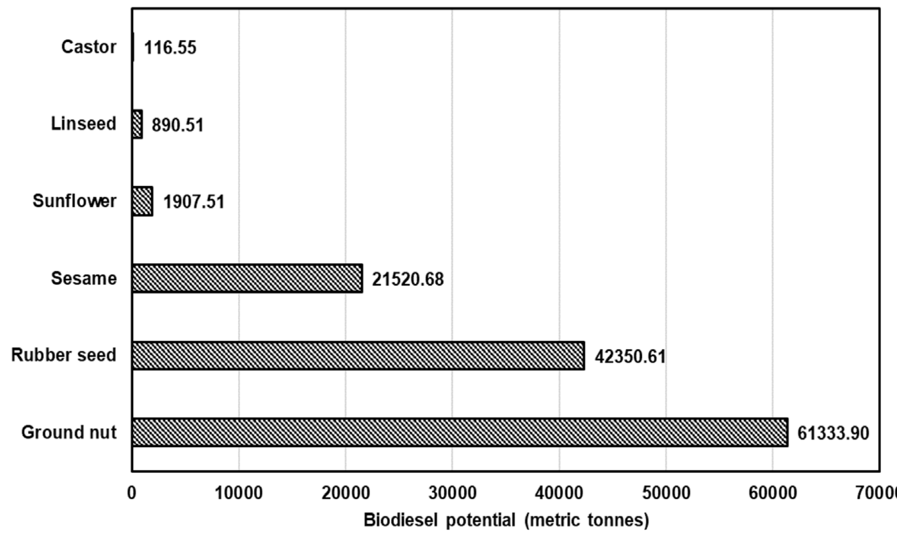

Fig. 4. Annual biodiesel potential in metric tonnes from edible and non-edible sources of Bangladesh.

Table 2
Annual production figures of main crops in Bangladesh in 2019–2020 (Department of Agricultural Extension, 2021).

Crop	Annual production (metric tonnes)	Residue	
		Field	Process
Rice	38,695,000	Straw	Husk
Corn	5,802,500	Stalk	Cob, Husk
Wheat	1,245,800	Straw	–
Jute	6,818,800	Stalk	–
Sugarcane	3,682,951	Leaves	Bagasse

Table 3
Values of FR, PR, collectable coefficient, and theoretical bioethanol conversion rates for the main crops in Bangladesh (Halder et al., 2014; Huda et al., 2014; Fang et al., 2018).

Crop	FR	PR	Collectable coefficient	Theoretical bioethanol conversion rate (g/kg)
Rice	1.757	0.23	0.79	521.09
Corn	2.08	0.20	0.88	487.89
Wheat	1.75	–	0.70	487.75
Jute	2	–	0.87	481.14
Sugarcane	0.3	0.25	0.70	432.62

Bangladesh Bureau of Statistics listed the northern district of Mymensingh with 1,206,728 acres of land coverage with rice, which is the highest in a district of the country (Anon, 2020b). However, the annual rice consumption by the local population was higher than the national production and as a result, the government had to depend on imports to satisfy the market demand (Shew et al., 2019). There are three major breeds of rice grown: aus, aman, and boro, with their planting and harvesting periods being pre-monsoon, monsoon, and dry season (Department of Agricultural Extension, 2021; Shew et al., 2019). The cultivation of rice results, primarily, in the following residues: rice straw, which is the dried stalk of the plant, and rice husk, which is the outer portion of rice grain. The straw is part of the field residue while the husk is formed in the mills (Huda et al., 2014). An estimated 58.504 million tonnes of residues were produced by rice farms in 2010-2011 (Huda et al., 2014). Abbas and Ansumali (2010) reported average cellulose content of 33.43% and average hemicellulose content of 20.99% in rice husk along with a bioethanol yield of 15% from rice husk. They also showed maximum theoretical bioethanol yields of 0.51g/g of glucose and 0.46g/g of xylose. The residues from rice in Bangladesh are estimated to yield 31.65 million metric tonnes of bioethanol, which is the highest potential among all other agricultural crop residues studied here. A study found 82% of the agricultural residue in Bangladesh was produced from rice cultivation and this amount could generate 27.73 million tonnes of bioethanol out of a total of 32 million tonnes based on the residue from seven major crops (Miskat et al., 2020).

5.3. Corn

Corn, also known as maize, is the second most cultivated crop in Bangladesh and an increasing number of farmers are shifting towards corn, hoping for greater profits by meeting the growing demands in the animal feed sector. It is a major constituent of animal feed and the crop's primary consumers are the country's livestock and fishery sector, with poultry farms consuming the most. National production of corn in 2019–2020 amounted to 5.8 million metric tonnes and its residues include plant stalk, husk, and corn cob (Huda et al., 2014; Department of Agricultural Extension, 2021). Corn has a high starch content (72%) and a single bushel of corn can lead to 2.7 gallons of bioethanol (Mosier and Ileleji, 2020). Based on the amount of corn residue generated in Bangladesh, there is a potential to obtain 5.68 million metric tonnes of bioethanol. Miskat et al. reported corn residue to have the second highest potential, after rice, with 4.13 million tonnes of bioethanol (Miskat et al., 2020).

5.4. Wheat

National wheat production for the year 2019–2020 stood at approximately 1.25 million metric tonnes with the north-western district of Thakurgaon having the highest land coverage of wheat at 73,776 acres (Department of Agricultural Extension, 2021; Anon, 2020b). However, local demand for wheat was more than six times higher resulting in a significant amount of imports of the crop (Mahmud, 2019). Wheat straw is the chief residue from the crop, and it ends up as a cooking fuel or as a construction material in rural homes. Wheat straw has cellulose and hemicellulose compositions of 48.57% and 27.7%, respectively. Saha et al. (2005) obtained 19 g of bioethanol from 78.3 g wheat straw, which was pre-treated with dilute sulphuric acid and enzyme saccharified. The use of wheat straw as a biofuel feedstock can lead to a production of 0.74 metric tonnes of bioethanol in Bangladesh.

5.5. Jute

Jute, the golden fibre of Bangladesh, saw annual production figures of 6.8 million metric tonnes in 2019–2020, and in 2019 a total of 109,073 acres of land were devoted for its cultivation (Department of Agricultural Extension, 2021; Anon, 2020b). Stalks, the major residue generated from the plant, generally end up as fuel or construction material in houses (Halder et al., 2014). With compositions of 42.52% cellulose and 12.24% hemicellulose, jute stalk possesses good potential to be a non-edible feedstock in the production of biofuels (Singh et al., 2020b). Utilization of this residue of jute is estimated to produce close to 5.71 million metric tonnes of bioethanol in Bangladesh.

5.6. Sugarcane

Sugarcane is considered to be the singular source of white sugar in Bangladesh and one of the most valuable cash crops farmed in the country (Rahman et al., 2016). It is mostly grown in the north-western regions of the country, being cultivated on 218,348 acres, and its use comprises of sugar and jaggery production, and consumption (Anon, 2020b). Cultivation of sugarcane results in leaves and bagasse as components in the waste stream. Bagasse production can reach 30% depending on the method of sugarcane processing (Sujata and Kaushal, 2020). Pippo et al. (2011) found processing a ton of sugarcane resulted in 140 kg of bagasse. In terms of chemical composition, sugarcane residues had 34.1–42.1% cellulose and 28.5–38.8% hemicellulose (Pereira et al., 2015). The country produced over 3.6 million metric tonnes of sugarcane in 2019–2020, and the waste stream of the crop has the capacity to generate about 0.61 million metric tonnes of bioethanol (Department of Agricultural Extension, 2021).

5.7. Bioethanol potential

Based on the agricultural residues of five major crops in Bangladesh, there is a potential to extract a combined 44.4 million metric tonnes of bioethanol. Rice has the highest potential, contributing 31.65 million metric tonnes or 71% of the total, since it is the most cultivated crop in the country, and production in the fiscal year of 2019–2020 stood at 38.7 million metric tonnes. Its adaptability to the different agricultural regions of the country has made it the most suited crop for cultivation (Nasim et al., 2018). The crop not only serves as the staple food of the population but also generates a large volume of residue that can become the country's largest bioethanol feedstock. After rice, the crops with the highest bioethanol potential are corn and jute, both resulting in around 12.8% of national production. The individual bioethanol potential of various raw materials is shown in Fig. 5. The Bangladesh Petroleum Corporation (BPC) sold 318,593 metric tonnes of petrol in the fiscal year of 2018–2019, with almost half going to meet the fuel demand in the transport sector (Anon, 2020d). Based on the bioethanol potential and in an optimistic scenario, the country can easily meet a 5% blending target with bioethanol sourced from agricultural residue.

6. Discussion

Biomass resources of Bangladesh, which consist of agricultural residues, forest residues, livestock residues, and municipal solid waste, are estimated to have an energy content of 1344.99 PJ (Halder et al., 2014). Biomass is primarily used as a fuel for cooking purposes in rural households with firewood being the most dominant type of fuel while agricultural residues were used the least (Baul et al., 2018). Besides serving as a fuel for cooking in a minority of rural households, agricultural residues are also utilized as feed for livestock while animal waste such as chicken skin or fat is not collected (Huda et al., 2014). The addition of biofuels would relatively increase the number of opportunities in rural areas. There will be more jobs available, increased income, diversification of cultivation, and investments in equipment. The new professions include in the fields of cultivation and collection of crops, transportation, and handling, and plant maintenance. The raw materials used do not require many farming skills, and the external resources needed are significantly low compared to the conventional crops of Bangladesh. Thus, a large workforce can be implemented; rural women can generate income alongside their household work. Arndt et al. (2010) discussed economic development possibilities, a rise in total exports, and simultaneously experiencing rural empowerment and poverty reduction due to biofuels. The rise in employment encourages people to migrate to or continue to reside in such local and rural economies, thus reducing people's tendency to move to city centres. Development in rural infrastructure occurs because of the need for the establishment of efficient biofuel production facilities and distribution mechanisms. Developing industries in such rural areas would increase secondary sector jobs due to the manufacturing process. The distribution and sale of such products would also expand the tertiary sector. Therefore, gradates of multiple fields of expertise would be demanded in these regions. The potential development of marketplaces for trading has the possibility to attract other utility companies to open businesses to meet the daily demands of white-collar workers. A significant contribution to the total tax payments would act as an incentive for the government to invest more in the transport industry's infrastructures. This includes making new highways, railways, and seaports. An initial case study of the European Union states that the accomplishments in bioenergy will increase 200,000 direct and indirect jobs (Grassi, 1999). Similarly, in Thailand, expected job generation would reach up to 382,400 people per year by 2022, with more than 90% of the employment occurring directly due to the agriculture of biofuels such as bioethanol and biodiesel (Silalertruksa et al., 2012).

Besides the socio-economic aspects, the use of biofuels also involves environmental effects. Bioethanol extracted from lignocellulosic biomass can result in a fall in greenhouse gas emissions (Sharma et al., 2020). Results of a life cycle assessment (LCA) of bioethanol from wheat straw exhibited higher reductions of greenhouse emissions in blended fuels with a higher composition of bioethanol (Borrion et al., 2012). Maga et al. (2019) compared 2G bioethanol from sugarcane bagasse with 1G bioethanol and the LCA showed 2G bioethanol had lower impacts in greenhouse

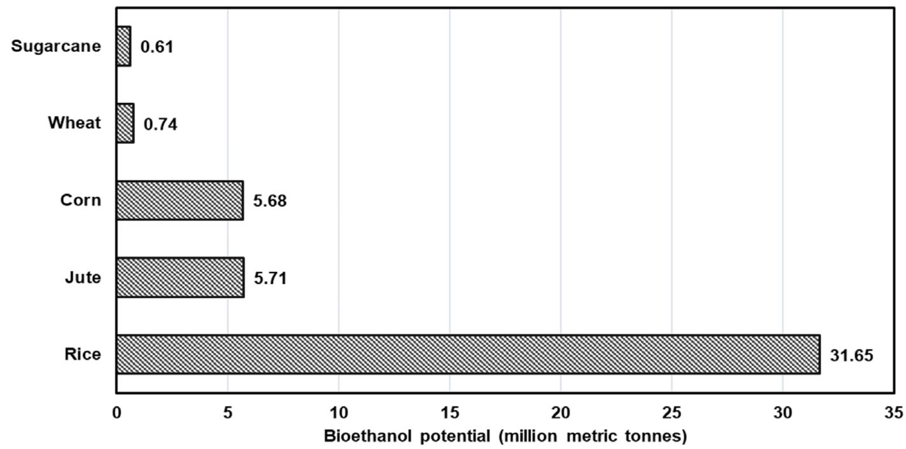

Fig. 5. Annual bioethanol potential in million metric tonnes from various crop residues of Bangladesh.

gas emissions, ozone layer depletion, and eutrophication. The only category in which 2G bioethanol had a higher impact than 1G bioethanol was resource depletion, which was caused by an increased demand of ammonium phosphate in the fermentation process. An assessment on bioethanol from rice straw in India also exhibited potential reductions in automobile emissions by blending with gasoline (Hassan et al., 2021). The actual environmental impacts of a biofuel can vary depending on the feedstock available in a location and the choice of conversion technology (Prasad et al., 2020). The blending of biofuels with gasoline and diesel can lower vehicular emissions and assist Bangladesh in reaching the 5% reduction target in the transport sector.

Feedstock prices of biofuels vary according to the region or conversion type being used. The government may also try to influence the price via the implementation of regulations to meet national priorities. The biggest challenge to making the price of biodiesel competitive with high-speed diesel is by ensuring feedstock accounts are kept as low as possible. The feedstock contributes 50 to 80% (Caesar et al., 2007) of the total price. Government subsidies or grants to farmers cultivating these raw materials may help to evolve the market. This would generate profitability to attract other producers and produce demand due to the competitive price. The final retail price will depend on other factors such as VAT, marketing margins, and carrying cost (Preechajarn et al., 2007). The climate of the geographical location also affects the production cost. Developing nations such as Brazil and Pakistan, where a warm climate is a common aspect, tend to have cheaper production costs in producing ethanol from sugarcane (Demırbas, 2017). Large volumes of production can lower operating costs when compared to smaller plants and, in developing countries, tend to make it a practical alternative fuel source compared to conventional petroleum fuels (Demırbas, 2017). Biodiesel, in particular, can be used directly as a fuel where the existing engines require some modifications, or it can be blended with clean diesel for use in engines with little to no modifications (Ogunkunle and Ahmed, 2019). One of the critical factors is the price, which acts as an inhibitor for the widespread usage of such a product. Instruments such as subsidies and tax cuts can make biofuels more competitive against conventional fossil fuels (Tilman et al., 2009).

The bioenergy industry simultaneously contributes to multiple sectors at both regional and national levels (Demırbas, 2017). There is a significant increase in the economic growth of the nation through an increase in earnings. The transportation and power sectors experience more robust energy security, thus reducing the dependency on imports. The import switching from expensive non-renewable energy sources to cheap renewable sources improves the total trade balance and reduces carbon dioxide emissions, and the economy as a whole experiences a rise in gross domestic product (GDP). With a growth in biofuels, Thailand is estimated to experience additional GDP growth of 150 million USD and national production of bioethanol alone has the potential to save imports of 2547 million USD per year (Silalertruksa et al., 2012). The aviation biofuel industry in Brazil can contribute up to 1100 million USD in the country's GDP depending on the supply chain and overall has positive socioeconomic effects (Wang et al., 2019). Industries such as transport and other services related to it have a significantly high energy-GPD elasticity (Burke and Csereklyei, 2016). The total aggregate energy-GPD tends to be higher in countries with high incomes. The fundamental reason being these economies have a great demand for commercialized products than traditional energy sources. Therefore, it can be assumed that a growing economy is likely to have more demand for fuels.

In Bangladesh, the transportation sector consumes just over half of the total crude oil, with the most dominant petroleum product being diesel fuel. Out of the 6,544,222 metric tonnes of petroleum product sold by the BPC in the fiscal year 2018–2019, almost 71% was diesel (Anon, 2020d). Most of the country's diesel consumption occurs in transport and the fuel is also used in diesel generators for irrigation purposes. For the same fiscal year, the BPC sold 266,988 metric tonnes of octane and 318,593 metric tonnes of petrol, mostly to the transportation sector. If the B5 blend (5% biodiesel with 95% diesel) is utilized, the country will see diesel imports dropping by 229,000 metric tonnes. The use of biofuel blended petrol and diesel in automobile engines can also reduce CO_2, CO, SO_2, and particulate matter emissions (Mahmudul et al., 2017). However, one disadvantage exists in the form of higher NO_x emissions from the burning of biodiesel. Since biodiesel has a high oxygen content, its calorific value is lower than that of diesel, but the high oxygen content allows the fuel to completely combust and actually enhances engine performance and lowering emissions (Ashraful et al., 2014). Biodiesel blends can also be mixed with small volumes of ethanol and the resultant diesel–biodiesel–ethanol fuel was found to have properties closer to that of pure diesel (Yasin et al., 2013; Al-Esawi et al., 2019). Kim et al. (2014) discussed the fuel consumption rate and efficiency of both commercial diesel and blended diesel in terms of kilometre per litre of fuel. The values are estimated to be roughly the same despite the variation of the different percentages of fuel proportions. However, a significant fall in the total emission of greenhouse gases can be seen.

While there are many advantages of biofuels, there exist multiple barriers to the growth of this sector. In India, there is a

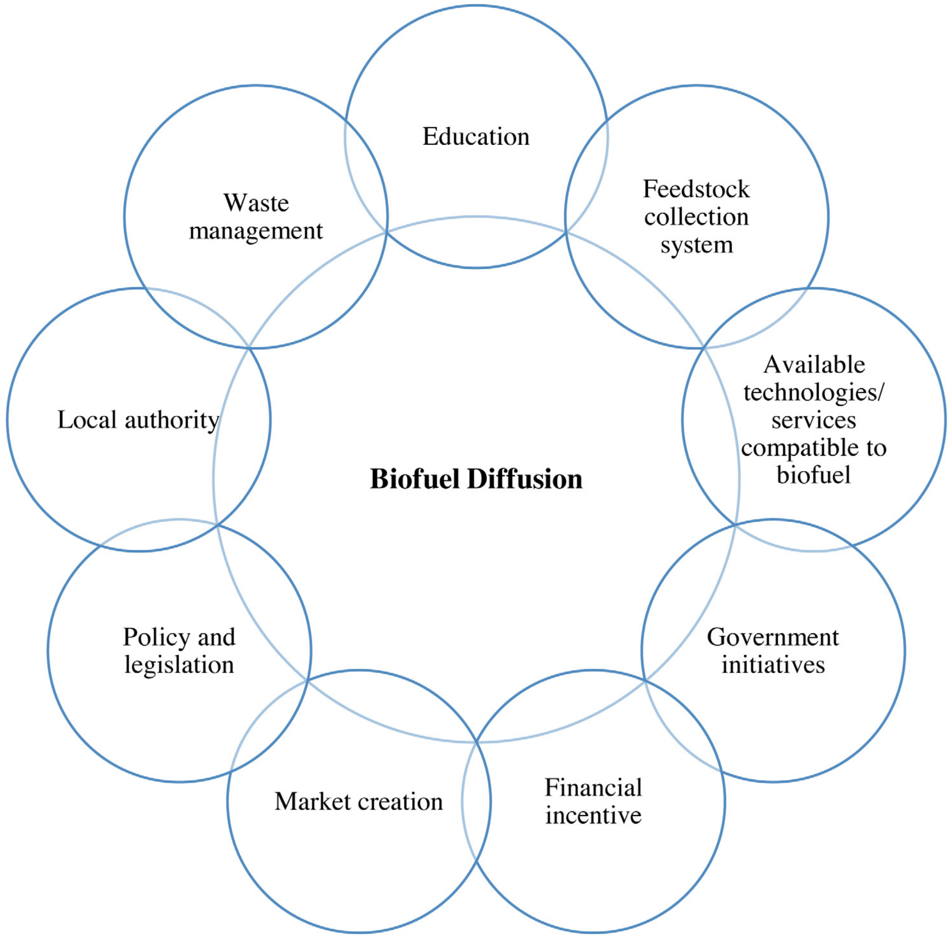

Fig. 6. Important actors to diffuse biofuels (inspired from Hasan and Ammenberg, 2019).

great discrepancy between predicted data and actual data. The cost of production of biodiesel turns out to be 20% to 50% higher than the national purchase policy price. The uncertainty of prices makes the market unstable (Mohan et al., 2006). There is an inadequate amount of land available for growing such crops. Normally, "wastelands" refer to the land which does not generate any revenue. There is a scarcity of such sort of uncultivated land that may be used for growing crops for biofuels (Kumar Biswas and Pohit, 2013). The unsustainable nature of seeds and low yield makes the cultivation of such crops a risky decision (Aradhey, 2016). The capital cost for producing bio-fuel and the operating costs for conversion is comparatively high (Chisti, 2008). In most Asian countries there are not many specialized storage facilities available to tackle the low-temperature properties of Jatropha and Palm biodiesel (Sarin et al., 2007).

6.1. Recommendations for biodiesel diffusion

Diffusion of biofuel depends on both national and local actors (Ammenberg et al., 2018). The government is considered as one main actors to diffuse the environmental technologies as they have a solitary authority of influence (Hasan and Ammenberg, 2019). Other important actors are public, private organizations, non-governmental organizations (NGOs), and media (Furtado et al., 2020). Urmee and Md (2016) highlighted the importance of sufficient local knowledge and skills for the diffusion of environmental technologies. Fig. 6 presents important actors for biofuel diffusion in a region.

Biofuel markets around the world are policy driven and it is crucial to have a congenial policy for implementing biofuel solutions in a region (Sinha et al., 2019). Bangladesh published its renewable energy policy in December 2008. The policy is mainly focused on power generation from renewable sources. However, there is little focus on biofuels, particularly, a lack of clear guidelines and roadmap to biofuel-based solutions. In fact, it is critical to have a well-structured policy that clearly defines the possible biofuel feedstock, the collection of those feedstocks, and the facilities needed for the extraction, treatment, and distillation of the biofuels. A policy of percentage-based volume mixture of bioethanol and biodiesel should be implemented in Bangladesh. Furthermore, the collection of potential biofuel feedstocks should be segmented depending on the nature of the feedstock. Crop residues are easier to collect since they are generated in large amounts at locations where they are already concentrated such as in the fields or the processing mills. On the other hand, 3G sources of chicken skin and used cooking oil are generated from multiple establishments such as slaughterhouses, restaurants, and residential areas. Specific urban zones or regions could be selected for testing bioethanol and biodiesel mixed fuel in the transportation sector of those areas.

Bangladesh can benefit by implementing policies divided into two types: technology-push and market-pull (Ebadian et al., 2020). These two types are complementary to each other, while technology-push supports research and development during the early stage, market-pull assists in the creation of a biofuel demand. Technology-push policies can drive innovation and with the combination of attractive financial packages and soft loans for farmers they can encourage growth in the biofuel sector. The government should consider introducing pricing schemes that encourage the distillation of biofuels and conduct awareness drives for the local population to drive their vehicles with biofuel-blended gasoline, petrol, or diesel. The existence of favourable support schemes is imperative for the development of the biofuel market. For the successful diffusion of biofuels, there is a need for the involvement of relevant actors: government, local population, future owners, media, and NGOs. Alongside fostering a biofuel market, the government must inform the urban population of the benefits of biofuels and generate public interest and willingness to adopt biofuel blended fuels. Instead of targeting one or two raw materials, Bangladesh should look to diversify the biofuel sources with an increased emphasis on 2G and 3G feedstocks. The use of 2G sources would avoid conflict with food crops while the use of 3G sources would transform waste, such as animal fat and used cooking oil, into useful products, thereby mitigating disposal issues.

Other countries show significant development of biofuel-based solutions driven by supportive policies. For example, Brazil, being one of the leaders in biofuels, provides a unique setting to increase the knowledge about biofuel policy and the interactions within and between the gasoline and ethanol markets (Cardoso et al., 2019). Policy in Brazil includes a mixture of 27% ethanol and 10% biodiesel by volume, and 100% hydrous ethanol is marketed in all gas stations in the country. In China, four biofuel standards have been set up since 2001: the Denatured Fuel Ethanol (GB, 18350) and Ethanol Gasoline for Motor Vehicles (GB, 18351) both initiated in 2001, Biodiesel Blend Stock (GBT,20828) initiated in 2007, and Biodiesel Fuel Blend (GBT 25199) initiated in 2010 (Hao et al., 2018). These standards have been updated over time. The biofuel policies have emphasized ethanol generation while biodiesel has been marginally promoted as the nation imports vegetable oils. In the United States of America, initial biofuel policies were focused on environmental protection but over time they expanded to include social and economic aspects while also adding vehicle emissions under the environmental protection sector (Soratana et al., 2014). Recent policies have started to transform to incorporate values of sustainability into their schemes. India set up a national policy in 2008, which was later reformed to a new one in 2018, to boost up the shares of biofuel use in the transport sector (Das, 2020). The new policy sets up various governmental incentives, subsidies, and grants as forms of financial support to encourage the growth of biofuels (Saravanan et al., 2020).

7. Conclusion & future research direction

This work investigated the technical potential of extracting biodiesel from agricultural residues and non-edible feedstocks of Bangladesh. The potential of extracting bioethanol from 2G feedstock such as agricultural residues was also reviewed. To the best of our knowledge, this study is novel considering that there is no prior study focusing on biofuel potentials in Bangladesh.

Results indicated that Bangladesh could generate a greater share of bioethanol than biodiesel due to the large amounts of agricultural residues of the major cultivated crops. The five major crops of rice, wheat, corn, sugarcane, and jute generated 87.19 million metric tonnes of residue in the form of husk, straw, cob, leaves, and bagasse in 2019–2020, and based on these, there is a potential to extract 44.4 million metric tonnes of bioethanol. Residues from rice, the most cultivated crop in the country, were found to be the most promising feedstock: generating 31.65 million metric tonnes of bioethanol, which is 71% of the total bioethanol potential from five major crops of the country. Jute and corn followed with bioethanol potentials of 5.71 and 5.68 million metric tonnes, respectively.

Among the biodiesel feedstock, ground nut and rubber seed exhibited the highest potentials, around 61,000 and 42,000 metric tonnes, respectively. Another promising 3G biodiesel feedstock is waste chicken skin, but its effective utilization requires a well-designed collection scheme. Proper utilization of various agricultural residues, oil crops, and waste animal fat to obtain biofuels can actively assist in lowering Bangladesh's oil imports and protect the local market from the volatile prices in the global oil industry. The result also highlights that non-edible sources can be utilized to achieve the country's 5% blending target. Alongside bioethanol, policymakers should consider 2G and 3G sources of biodiesel for blending, as diesel is one of the major imported petroleum products sold by the BPC, with the transport sector being the chief consumer. The results can also assist the respective authority in planning biofuel extraction plants based on the geographical distribution of different crops across the country.

Nonetheless, despite of a great potential in Bangladesh, there has not been any significant growth observed in the biofuel sector. In light of this, in a recent study, Hasan et al. (2020) discussed the bottlenecks to biofuel diffusion in Bangladesh, thus pointing to several technical, social, market, economic, and policy barriers. Similarly, Mondal et al. (2010) argued on lack of public awareness as an important barrier to diffusion of renewable energy technologies in Bangladesh. Therefore, case studies and/or pilot projects should be performed to further understanding the barriers to large-scale application of biofuel solutions.

Finally, there is also an inherent necessity to focus on suitable mechanism and business models for the successful diffusion of biofuel. It would be interesting to observe how the business models alleviate the biofuel diffusion in a densely populated country like Bangladesh ensuring environmental sustainability and market expansion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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