



Review article

A review of non-edible indigenous seeds feedstock in Bangladesh for biodiesel: Production, fuel properties and combustions performance

Ehsanul Hoque ^{a,1}, Md Ismail Hossen Emon ^{a,b,1}, Md Tawfiq Anik ^a, Mohammad Ariful Islam ^a, Ikramul Hasan ^c, Tanvir Ahmed ^a, Zia Ullah Arif ^d, Mokarram Hossain ^e, Mohammad Ismail ^{a,f,*}

^a Department of Applied Chemistry & Chemical Engineering, University of Dhaka, Dhaka 1000, Bangladesh

^b Bangladesh Reference Institute for Chemical Measurements, Dhaka 1205, Bangladesh

^c Department of Macromolecular Science & Engineering, Biointerfaces Institute, University of Michigan, MI 48109, USA

^d Department of Mechanical Engineering, University of Southampton, SO17 1B, Southampton, UK

^e Department of Mechanical Engineering, Faculty of Science and Engineering, Bay Campus Swansea University, SA1 8EN, Swansea, UK

^f Vice Chancellor, Noakhali Science and Technology University, Noakhali-3814, Bangladesh

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ABSTRACT

The demand for energy has been escalating daily due to rapid population growth and economic expansion. Heavy reliance on non-renewable energy sources causes significant environmental harm and results in high costs, making renewable resources essential. Biodiesel, a non-toxic and environmentally friendly fuel, closely resembles conventional fossil fuels. It is derived from renewable sources such as palm oil, animal fats, and non-edible seeds. Biodiesel offers notable benefits, including reduced generation of greenhouse gases (GHGs) and hazardous air pollutants. Despite these advantages, widespread adoption of biodiesel remains challenging. This study explores the various non-edible seeds obtained from indigenous plants in Bangladesh, physico-chemical properties of these extracted oil, biodiesel production, and their engine performance study. Among the reported fifteen seeds, the oil content was found to be the highest in Eucalyptus seed (50%–60%), followed by Jatropa, Rubber, Mahua and so on. Stearic acid (C18:0), Oleic acid (C18:1) and Linoleic acid (C18:2) were commonly found in all the seeds whereas the maximum content of palmitic acid and Oleic acid was found in cotton seed oil. The biodiesel yield during the trans-esterification process was found about 95%. A Biodiesel blend of 15%–20% with commercial diesel was found acceptable for smooth performance of the existing engines. The emission of CO, hydrocarbons, smokes etc. reduced by 10%–50% while using biodiesel blend whereas the emissions of CO₂ and in some cases, NOx increased by 10%–20% more than that of the commercial diesel.

1. Introduction

Energy remains one of the most significant factors in the economic growth and development of a country. Currently, in Bangladesh, the main indigenous source of energy is natural gas, with other fossil fuels such as coal and some petroleum [1]. The local production of natural gas is likely to be exhausted in the near future. Considering the growing energy demand and the uncertainty surrounding the sustainability of the current primary energy source, it is imperative to look for alternative renewable energy sources like biofuel to ensure future energy security.

Biofuel, a renewable source of fuel, is derived from biomass materials and can be liquid, solid or gaseous. Biodiesel, one of the most common liquid biofuels, contains long-chain fatty acid esters and can be produced from different plants and animal sources, including raw

or used edible vegetable oils, non-edible vegetable oils, and animal fats. Although most vegetable oils can be directly used in diesel engines, it is not advisable because of their high viscosity, which results in poor atomization and incomplete combustion. This leads to poor performance, nozzle clogging, excessive engine deposits, thick smoke emissions, ring sticking and potential engine stalling [2]. This issue can be solved by turning vegetable oils into biodiesel, which reduces viscosity and increases performance and efficiency [3]. Due to the challenge of global depletion in food supply associated with the use of edible seeds for biodiesel production, non-edible seeds are considered as more promising feedstock. In biodiesel production, fatty acids in the extracted raw oil are converted into mono alkyl esters, such as methyl ester or ethyl ester through a transesterification reaction in the presence of a catalyst [3], as illustrated in Fig. 1.

* Corresponding author.

E-mail address: m.ismail@du.ac.bd (M. Ismail).

¹ Co first author.

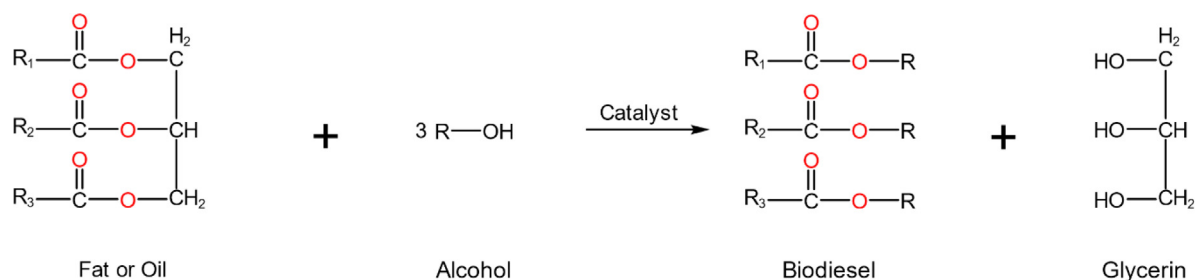


Fig. 1. Transesterification reaction for biodiesel production.

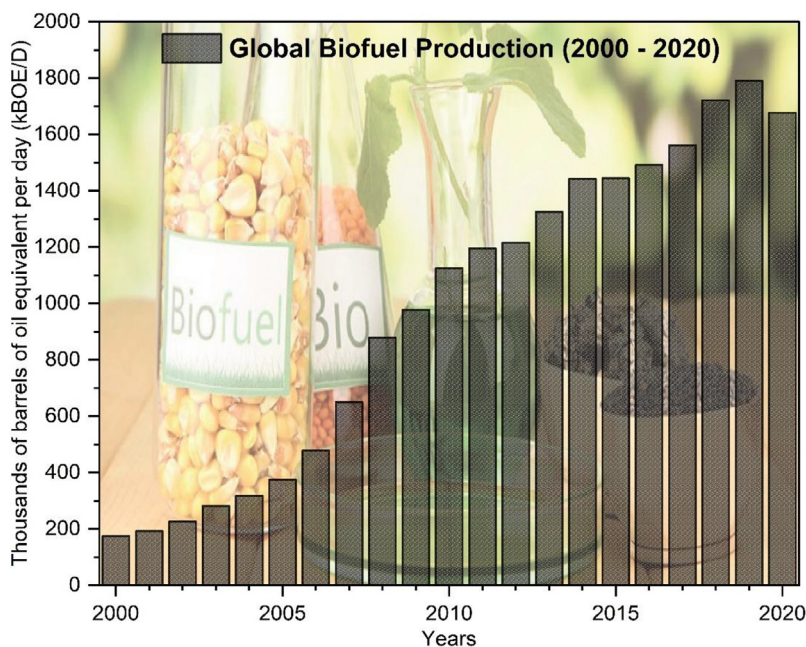


Fig. 2. Global biofuel production scenario during 2000–2020 [5].

Commercial production of biodiesel still has some technical limitations, including lower oil content in the feedstocks, efficiency of catalysts, and lower yield in large scale production, among others [4]. With the gradual overcoming of these technical limitations, global biodiesel production has increased steadily over the last two decades, except in 2020, when it decreased by 6% due to the impact of COVID-19 [5], as shown in Fig. 2. Global biofuel production was rising until 2019, reaching 1790 barrels of oil equivalent per day (kBOE/D), which was 4% higher than the previous year [5], and providing 3% of the world's fuel consumption [6].

To reduce dependency on fossil fuels, the International Energy Agency (IEA) suggested that biofuels should meet 25% of the world's fuel demands in transportation by 2050 [6]. For this to happen, global biofuel production and consumption must grow by 10% annually for the next 10 years, although only 3% annual growth is expected for the next 5 years. To achieve a Sustainable Development Scenario (SDS), biofuel consumption is expected to almost triple by 2030. However, global biofuel production is not growing quickly enough to meet the SDS demand.

Globally, Malaysia, USA, Philippines, Indonesia, Argentina, Brazil, Netherlands, Germany, Belgium, and Spain are considered the top ten countries in terms of biodiesel production potential [7]. Among developing countries, Nepal ranks in the top ten with a biodiesel potential of 49.04 million liters (L), whereas Bangladesh has a potential of 31,217 L [7]. According to the US Energy Information Administration, biodiesel production in Bangladesh was 0 Mb/d up to 2019 [8].

The zero-biodiesel production rate and comparatively lower potential for biodiesel production in Bangladesh can be attributed to significantly less focus by academic and industrial research, as well as government policy towards this area. Globally, until 2020, the total number of scholarly documents in the area of biodiesel production was 24,353, as per Scifinder[®] (Chemical Abstracts Service, American Chemical Society, Columbus, OH, USA) search, of which Bangladesh contributed only 17. This indicates insufficient research in this area.

The number of published articles from 2010 to 2020, as shown in Fig. 3, indicates the attention given to this area by researchers around the world. According to the annual report 2019 published by the Ministry of Power, Energy and Mineral Resources of Bangladesh, there are only three solar-based power plants with a total capacity of 30 MW and one hydro power plant with 230 MW capacity. These solar and hydro energy are the only forms of renewable energy that contribute to electricity production without any contribution from any sort of biofuels [9]. However, a master plan for the power system published in 2016 by the same ministry suggests that the government is planning to set up a biomass-based fuel production system with a total capacity of 275 MW. Despite this plan, there is no systematic review on the potential non-edible feedstocks for biodiesel production specifically for Bangladesh.

In this review, indigenous non-edible seeds of Bangladesh have been identified and explored for their potential application in biodiesel production. The physico-chemical properties of the extracted raw oil from different feedstock and those of the produced biodiesel are evaluated.

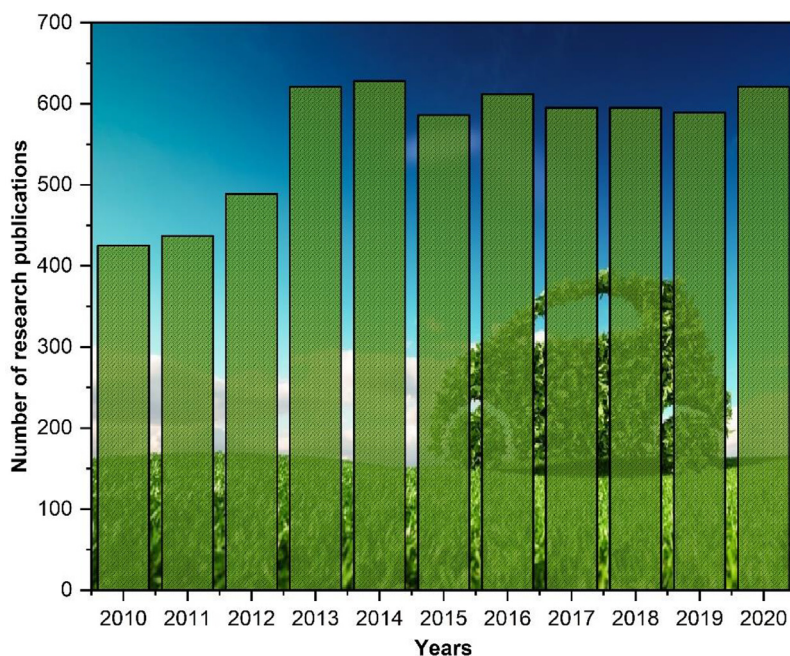


Fig. 3. Number of research publications on biodiesel production worldwide in 2010–2020 [10].

Table 1

English name, local name, and scientific name of the seeds under study[11].

Sr#	English name	Local name	Scientific name
1.	Jatropha	Sada mander/Jamal gota/ Arenda/ Ratan jot	<i>Jatropha curcas</i>
2.	Karanja	Karanja/ Koroch/ Titgila	<i>Pongamia pinnata</i>
3.	Mahogany	Mahogany	<i>Swietenia macrophylla</i> <i>Swietenia mahagoni</i>
4.	Castor	Veranda/ Venna	<i>Ricinus communis</i>
5.	Sal	Sal/ Shal/ Gojari	<i>Shorea robusta</i>
6.	Rubber	Rubber	<i>Hevea brasiliensis</i>
7.	Cotton	Tula	<i>Gossypium hirsutum</i> <i>Gossypium herbaceum</i>
8.	Nageshwar	Nageshwar/ Nagkesar/ Ceylon ironwood	<i>Mesua ferrea</i>
9.	Neem	Neem	<i>Azadirachta indica</i>
10.	Pithraj	Pithraj	<i>Aphanamixis polystachya</i>
11.	Mahua	Mohua/ Madhuca	<i>Madhuca longifolia</i> <i>Madhuca indica</i>
12.	Sugar Apple	Ata	<i>Annona squamosa</i>
13.	Eucalyptus	Eucalyptus	<i>Eucalyptus species</i> (Many different species)
14.	Shiyal Kata	Shiyal Kata	<i>Argemone mexicana</i>

This article also reviews the different catalysts used for the transesterification process. An assessment of the engine performance and greenhouse gas (GHG) emission characteristics of various biodiesels are reported and provided suggestions for Bangladesh on the potential use of non-edible seed oil for biodiesel production.

2. Non-edible seeds in Bangladesh, their biology, and physio-chemical properties

2.1. Commonly available non-edible seeds in Bangladesh

A wide range of edible and non-edible seeds are available in Bangladesh; however, this review focuses on some selected indigenous (non-edible) seeds, which are illustrated in Table 1:

Images of the selected common non-edible seeds available in Bangladesh are presented in Fig. 4 and a brief overview of the biology of these seed plants is illustrated in the following section.

2.2. Biology, distribution and chemistry of non-edible seed trees under study

2.2.1. Jatropha

Jatropha tree, a deciduous species belonging to the Euphorbiaceae family, usually grows 5 to 7 meters in height [12]. It can grow even on gravelly, sandy, and saline soils and withstand extreme drought and light frost conditions [13,14]. Its seeds contain approximately 79% unsaturated fatty acid, 21% saturated fatty acid and other compounds, such as saccharose, raffinose, stachyose, glucose, fructose, galactose, and protein [15,16]. The oil extracted from Jatropha has a very high saponification value and is extensively used in soap production. It is also used as an illuminant due to its smoke-free burning properties, while the bark is used to produce a dark blue dye for clothing [13]. After detoxication, the seed cakes (residues from oil extraction) can be valuable as animal feeds as well as fertilizers [14].



Fig. 4. Images of various non-edible seeds of Bangladesh selected under focus.

2.2.2. Karanja

Karanja tree, also known as Koroch in Bangladesh, belongs to the Leguminosae family. It is a perennial with a fast growth rate and medium texture, reaching an average height of 35 to 40 ft [17]. Karanja seed contains 20–50 wt% oil, which contains 20.5% saturated fatty acids and 79.4% unsaturated fatty acids [17]. In addition to producing biodiesel, Karanja seeds have medical uses for treating keloid tumors, hypertension, rheumatic arthritis, skin ailments, pectoral diseases, inflammations, hemorrhoids, chronic fevers, anemia, febrifuge, bronchitis, and whooping cough. These seeds can also be used as insecticide and fertilizer after oil extraction [17].

2.2.3. Mahogany

Mahogany tree, which belongs to the Meliaceae family, is a medium-sized, deciduous, and economically important tree. In Bangladesh, it is abundant in both plane lands and hilly areas [18]. The tree bears brown, woody capsule fruits which contain numerous winged seeds. Mahogany seeds and barks are sometimes used as a source of vitamins, for controlling blood sugar, treating constipation and menstrual pain and as an insect repellent. A study conducted in 2017 shows that one ton of Mahogany seeds from Bangladesh can produce approximately 420 liters of bio-oil and 352 liters of biodiesel [19].

2.2.4. Sal

Sal trees, a deciduous plant of the family of Dipterocarpaceae, reach heights of 18–30 meters [20]. These seeds are round, coated and feature five distinct wings. It is mostly valued for its resinous and durable timber, which is used in the construction of door and window frames. Oil extracted from Sal seeds has applications in lubrication, paints and pigments [21]. De-oiled Sal seed cake can also be used as a feed for fish [22] and for protease production [23], which is useful in kitchen wastewater treatment. Additionally, Sal fat can be used as an alternative to cocoa butter in confectionary [24].

2.2.5. Rubber

The Rubber tree belongs to the Euphorbiaceae family which is a forest-based tree that can grow up to 34 m in height. It is largely produced in Malaysia, India, Thailand, Indonesia, and Bangladesh [12].

Latex, the main product of rubber trees, is used in adhesives, chemicals, automotive, mining, agriculture, pharmaceuticals and consumer industries to manufacture a variety of products [25]. Additionally, oil extracted from rubber seed, similar to linseed oil, can be processed for use in varnishes, paints and soaps [25]. The residual cake from rubber seed can be used as feed for cattle and poultry after the removal of the toxic cyanohydric acid [25].

2.2.6. Cotton

Cotton which belongs to the family of Malvaceae, is collected mainly from two species: *Gossypium hirsutum* and *Gossypium herbaceum*, both widely cultivated all over the world [26,27]. The primary use of cotton trees is to produce cotton, which is subsequently used in textile production. Cotton seeds contain 17–25 wt% of oil [12], and seed cake contain 8%–12% of oil, 37% fermentable polysaccharides, and 16% lignin [28]. Biodiesel with higher ester content and hydrogen can be produced from cotton seed cake [28,29]. Bio-oil production from cotton seed cake is possible through pyrolysis [30], and bioethanol can also be produced from cotton seed hulls [31]. Additionally, cotton has many medicinal uses, including treatment for irregular bleeding, gastrointestinal problems, haemorrhages, diarrhoea, nausea, fevers and headaches [27].

2.2.7. Nageshwar

Nageshwar tree, also known as Nagkesar, belongs to the Calophyllaceae family. This tree is native to the wet tropical parts of Sri Lanka, Southern Nepal, India, Myanmar, Thailand, Philippines, Malaysia and Sumatra [32]. The lipid content of its seeds is 67%–70%, which is higher compared to other non-edible seeds, making it a rich source of lipids and protein [33]. The seeds have been used in traditional medicinal treatments in Bangladesh for ailments such as rheumatism, vomiting, cough, dysentery, fever, and itch since ancient times [33].

2.2.8. Neem

Neem tree belongs to the Meliaceae family. It can easily burgeon in saline, clay, dry, shallow, alkaline, and even calcareous soil conditions [12]. The tree can withstand a maximum temperature up to 48 °C as well as extremely dry conditions [25]. A matured neem tree can

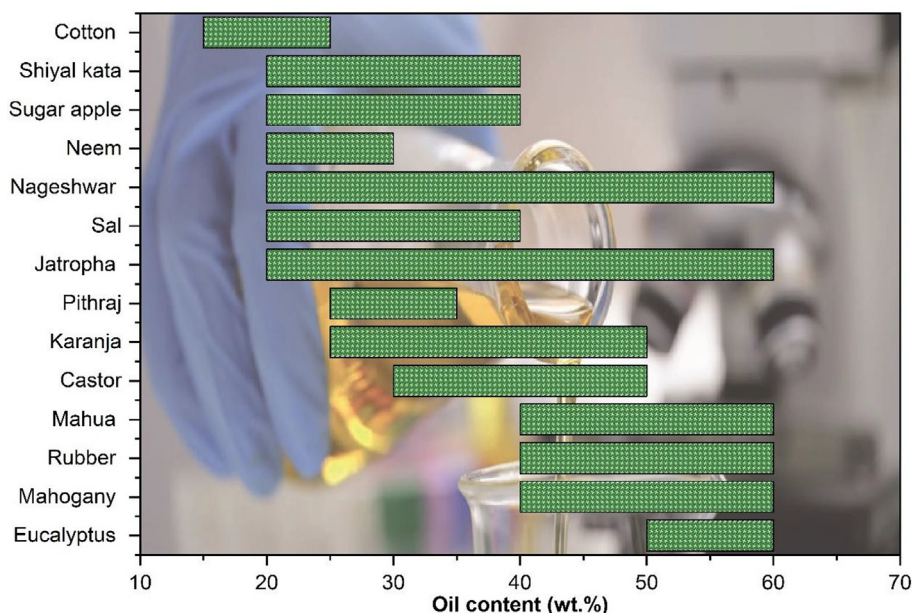


Fig. 5. The oil content of various non-edible seeds in Bangladesh [34–48].

provide 30–50 kg of fruits, and in Bangladesh, around 30,000 tons of oil per annum can be extracted from neem seeds [25]. Despite all parts of the neem tree having pharmaceutical value, it has other uses as well. Its seed cake, enriched with nitrogen, phosphorus, and potash, can be used as organic fertilizer. It is reported that using neem seed cake as an alternative to urea and superphosphate fertilizers can reduce the need for these fertilizers by 25%–50% [25].

2.2.9. Pithraj

Pithraj tree, another well-known tree in Bangladesh, belongs to the Meliaceae family. It is an evergreen tree with a large canopy and an umbrella-shaped crown that can reach a height of 25–35 meters [49]. Each fruit of this tree contains 2–4 reddish-black seeds with a length of 1.0–1.5 cm and a diameter of 1.5–5.0 cm, with approximately 25%–35% oil extractable from the seeds [50]. The tree has medicinal characteristics and is used to treat conditions such as rheumatism; it also has astringent, insecticidal, and antifeedant characteristics [49].

2.2.10. Mahua

Mahua (both *Madhuca longifolia* and *Mahua indica*) is a deciduous nature tree in the Sapotaceae family [51], Native to the dry tropical and sub-tropical regions of the Indian sub-continent [52]. Most parts of the tree are used for herbal medications by the tribes of India and Sri Lanka. The edible Mahua flowers are used in the production of alcohol and vinegar. Mahua seeds contain about 40%–60% oil, suitable for soap production and lubricating purposes [53]. Furthermore, Mahua seed cake, rich in nutrients (N, P and K) and serving as a bio-pesticide is used as cattle feed and fertilizer [54].

2.2.11. Sugar apple

Sugar apple or custard apple tree belongs to the Annonaceae family. The nearly round fruits have a thick peel composed of knobby segments, usually pale green, gray-green, or bluish green in color [55] and contain sweet whitish pulps. Fruits of the *Annona squamosa* tree are usually eaten in raw form. Their leaves and roots are used in traditional medicines to treat common health problems and are also crushed and applied for wound healing. It has been reported that the seeds contain around 26.8% oil [56], but they are not used for purposes other than cultivation.

2.2.12. Eucalyptus

Eucalyptus, a genus of trees in the Myrtaceae family, include species such as *E. camaldulensis*, *E. tereticornis*, *E. brassiana*, which can be found abundantly throughout Bangladesh. These fast-growing trees are found worldwide and are valued for their timber. Eucalyptus trees are used for pulpwood, honey and oil production, as well as for ornamentation, timber, and firewood. These seeds are collected from cup-shaped fruits and dried, with an oil content of around 55%–60%, higher than most non-edible seeds [57,58]. Eucalyptus oil extracted from leaves and seed is used as an industrial solvent, and antiseptic for deodorizing in mosquito repellents and in biofuel production. Furthermore, any part of the Eucalyptus can produce dye, with extracted colors ranging from yellow, orange and green to chocolate and deep rust red. Their remains can be used as fertilizers [59].

2.2.13. Shiyal kata

Shiyal Kata, belonging to the Papaveraceae family, is an annual herb with erect, spiny stems and leaves, commonly found growing as a weed in open waste grounds. Seeds are black in color with some toxic alkaloids. The Argemone Mexicana seed contains about 30% oil [60]. Moreover, the seeds contain various toxic alkaloids, which have important medicinal values and can be used externally on the human body [61].

2.2.14. Castor

Castor bean tree, belonging to the Euphorbiaceae family produces seeds with an oil content ranging from 42% to 54% by weight, with an average of about 46% oil [62,63]. Castor oil has numerous applications, including manufacturing waterproof fabrics, removing grease from fabrics, moisturizing in the textile industry, and serving as a lubricant in the steel industry. It can also be used to produce high-performance motor oil and brake fluids in the automotive industry. Additionally, castor oil functions as a softener in the tanning industry and is used in the production of hydraulic devices, artificial leather, linoleum, insulators, powders, fatty acids, enzymes, varnish, plastic fabrication, and various compounds such as solvent, paints, rubbers, and chemical inputs [63,64].

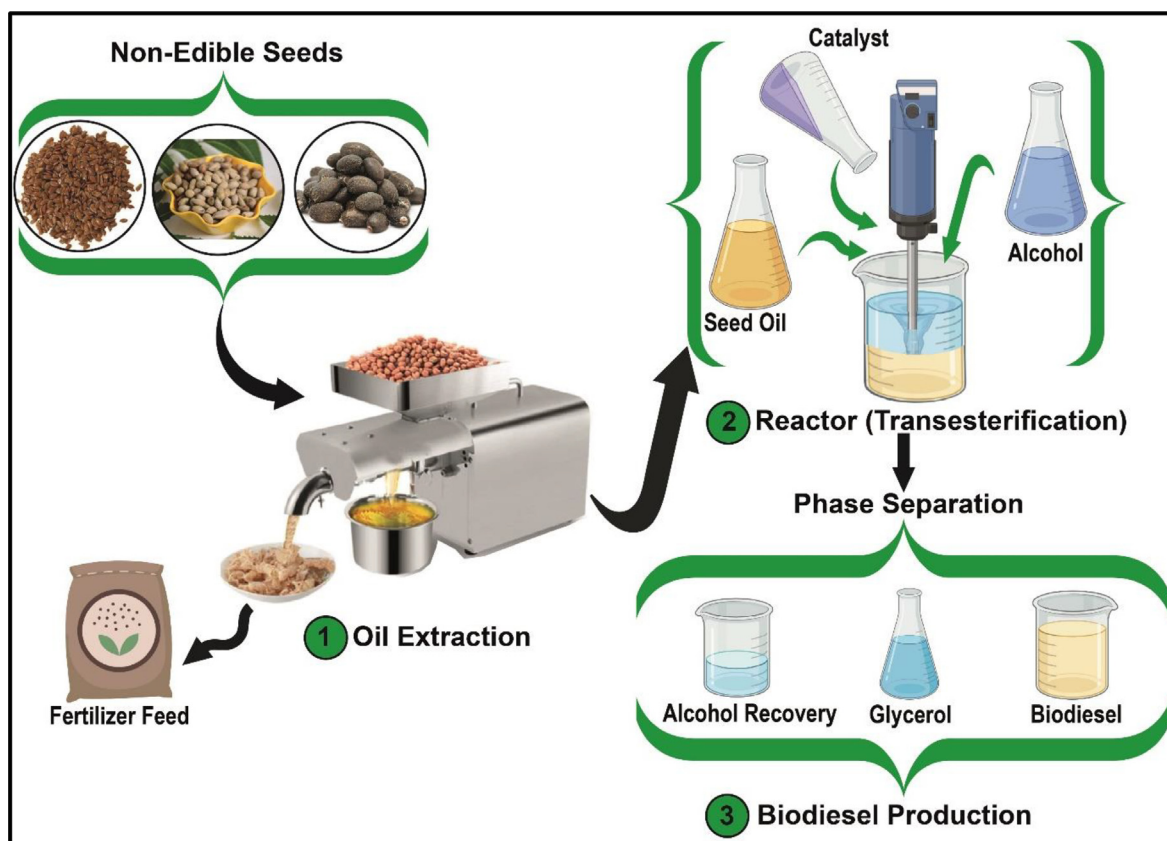


Fig. 6. A schematic flow diagram of the biodiesel production process from non-edible seeds.

2.3. Oil content of selected non-edible seeds

Oil contents of various non-edible seeds are visualized through a floating bar chart in Fig. 5. All of the non-edible seeds chosen for this study have a relatively high oil content. Among the selected seeds, the highest oil content was found in Eucalyptus seeds (50%–60%), while the lowest was reported in cotton seeds (15%–25%). Furthermore, seeds of Mahogany, Rubber, Mahua, Castor, and others contain relatively high oil content, following Eucalyptus.

The widest variation in oil content was reported for *Jatropha* seeds. This variation can result from factors including land geography, soil fertility, seed quality, weather conditions, and irrigation. The oil content in seeds plays a vital role in biodiesel yield, as it serves as the primary feedstock converted into biodiesel through the transesterification process.

2.4. Fatty acid content and their compositions in seed oil

Fatty acid contents of seed oils from various non-edible resources are presented in Table 2, detailing the types and percentages of different fatty acids which influence their quality and usability for biodiesel production. In non-edible oils, C16 and C18 fatty acids are commonly found, though some feedstocks contain substantial amounts of other fatty acids [65]. The consistency of biodiesel is primarily affected by the types and relative concentrations of fatty acids. For instance, mono-unsaturated fatty acids in biodiesel blends increase combustion efficiency, fuel flow characteristics, and stability [66]. In contrast, the inclusion of a higher proportion of polyunsaturated fatty acids in the biodiesel sample can substantially decrease oxidative stability due to their susceptibility to autoxidation [67]. Moreover, decanoic acid can improve oxidative stability and fuel flow, while saturated fatty acid, such as alkyl esters, can increase cetane number, stability, and the cloud point of the fuel [68,69].

Castor oil, also known as ricinoleic acid triglyceride, contains 70%–90% hydroxy functionality of a fatty acid. Ricinoleic acid, a common hydroxy fatty acid, can undergo different reactions to form numerous derivatives and is used in applications such as printing ink, pigments, dyes, and textile finishing. Cotton, Eucalyptus, and Nageshwar seeds contain significant amounts of oleic acids, while rubber and Shiyal Kata seed oils are rich in linoleic acid, indicating lower kinematic viscosity, oxidation stability, and higher heating value (HHV) [81]. In contrast, stearic acid and palmitic acid are found in the highest amounts in Sal and Cotton seed oils, respectively, suggesting a higher cetane number [82].

2.5. Biodiesel production process

Naturally grown non-edible seeds are generally dehulled, dried, and then processed to extract oil using various techniques such as mechanical expelling, Soxhlet extraction, or ultrasonication. Temperature and extraction time are crucial factors in maximizing oil yield [57]. After removing suspended impurities through filtration and other processes, the oil is prepared for esterification and transesterification processes to produce biodiesel. The presence of free fatty acid (FFA), indicated by the acid value, is critical in determining the suitability for direct base-catalyzed transesterification. A higher acid value necessitates an acid-catalyzed esterification process to reduce the FFA. A detailed but simplified flow sheet of the biodiesel production process is illustrated in Fig. 6.

To carry out the esterification process, an esterifying agent such as methanol or ethanol and a catalyst like H_2SO_4 are required [70]. Factors such as the acid value (FFA content), emulsifier amount, catalyst type, reaction temperature, and reaction time are important for assessing the esterification process. After esterification, the oil, once separated, is used in the transesterification process. During transesterification, variables such as the weight percentage of the limiting reactant

Table 2
Typical fatty acid compositions of various non-edible seed oil resources.

Seed	Myristic acid (C14:0)	Palmitic acid (C16:0)	Stearic acid (C18:0)	Oleic acid (C18:1)	Linoleic acid (C18:2)	α -Linolenic acid (C18:3)	Ricinoleic Acid (C18:1OH)	Arachidic acid (C20:0)	Behenic acid (C22:0)	Ref.
Jatropha	1.4	14.5	9.8	41.0	30.0			0.4		[68,70]
Karanja	0.45	10.8	8.7	46.0	27.1	6.3		0.8	3.2	[17,68]
Mahogany		13.6	15.8	25.9	30.1	13.5		1.1		[71]
Sal		6.5	47.5	35.0	1.5	0.3		7.8		[20,24]
Rubber		10.2	8.7	24.6	39.6	16.3				[72,73]
Cotton	1.6	29.4	1.2	60.0	1.6					[74]
Nageshwar	2.4	10.9	14.2	56.0	13.7			3.0		[33]
Neem		18.1	18.1	44.5	18.3	0.2		0.8		[75]
Pithraj		18.4	11.8	18.3	26.7	23.2				[50,76]
Mahua		22.5	23.2	42.5	9.5			1.5		[53] [51]
Sugar apple		22.2	3.9	41.9	28.7	1.6			2.0	[56,77]
Eucalyptus		26.2	6.3	57.2	9.5					[19,20]
Shiyal kata		14.7	6.7	40.0	36.6	0.3		0.3	0.2	[60,78]
Castor			1.5	4.2	1.5	1.0	89.5			[79,80]

Table 3
Production of biodiesel from different seeds using several types of catalyst.

Seed	Process type	Catalyst	Yield (%)	Ref.
Neem	Ultrasonic transesterification	0.75% (V/V) H ₂ SO ₄ , 1.2% KOH, Ultrasonic processor (20–36 KHz)	98.01	[83]
	Transesterification	1.7 wt% CBP ^a , 1.3 wt% Li-CaO/Fe ₂ (SO ₄) ₃	99.8	[84]
Castor	Transesterification	0.73% KOH, 6 wt% MgO-UREA-800	96.5 –98	[85,86]
Shiyal Kata	Transesterification	Cryst. MnCO ₃ (1%), Ca-complex (5 wt%)	98 –99.99	[78,87]
Jatropha	Ultrasonic transesterification	3 wt% Na/SiO ₂	98.53	[88]
	Transesterification	5 wt% strontium doped CaO/MgO	99.6	[89]
Sal	Transesterification	8.9 g/kg KOH, 0.25 wt% NaOH	92 –99	[90,91]
Eucalyptus	Ultrasonic transesterification	110.25 W ultrasonic power (29.54 kHz frequency)	96.73	[58]
	Transesterification	0.45% KOH	95	[92]
Rubbers	Transesterification	H ₂ SO ₄ (0.5 wt%), KOH (0.6 wt%), Al ₂ O ₃ (4 wt%) + eggshells, Limestone (5 wt%)	97–99	[93–96]

^a Calcined banana ash derived from banana peels.

relative to the catalyst, reaction temperature, and time significantly impact the yield of biodiesel. For instance, the optimal conditions for transesterifying Jatropha seed oil were found to be 50% (w/w of oil) methanol and 0.80% (w/w of oil) NaOH as a catalyst, with a reaction time of 90 min at 60 °C and continuous stirring at 400 rpm [70]. The biodiesel produced, which forms the top layer of the reactor, must be separated from the byproducts (glycerin, found at the bottom layer) and followed by washed with water. Various types of catalysts can be used for biodiesel production. Table 3 lists some common catalysts used in biodiesel production processes.

2.6. Physico-chemical characteristics of seed oil from non-edible resources and the production of biodiesel

A variety of physio-chemical tests are required to explore the fuel properties of biodiesel produced from the selected seeds described in the previous section. Important properties for qualitative analysis include viscosity, density, acid number, flash point, cloud point, pour point, cetane number, and calorific values. The calorific values of various seed oils and the biodiesel produced from them are shown in Fig. 7. Furthermore, various physico-chemical properties of seed oils and biodiesel produced from different seeds, are presented in Table 4.

2.6.1. Calorific value

The calorific value of a fuel, which reflects the heat produced by the complete combustion of a specified quantity, is directly proportional to its efficiency. Seed oils and biodiesels usually have lower calorific values than conventional diesel due to their higher oxygen content. Among the various seed oils, neem seed oil has the highest calorific

value at 40 MJ/Kg. Among the biodiesels produced, those from Karanja (42 MJ/Kg), Cotton (41 MJ/Kg), and Eucalyptus (42 MJ/Kg) have calorific values closer to that of commercial diesel (44 MJ/Kg). A comparison of the calorific values of seed oils and biodiesels with commercial diesel is depicted in Fig. 7.

2.6.2. Kinematic viscosity

Kinematic viscosity which indicates the flow properties of biodiesel, significantly affects the engine performance by measuring the fuel's internal resistance to gravitational force. Highly viscous fuel exhibits reduced flow, taking longer time to reach the combustion chamber and mix with air during the intake stroke [12]. Among various seed oils, Eucalyptus seed oil has the lowest kinematic viscosity of 3.8 cSt, comparable to diesel fuel (4.1 cSt), while Castor seed oil has the highest viscosity at 107 cSt. Biodiesel produced from Castor oil has the highest viscosity of 15 cSt, whereas biodiesel from Eucalyptus seed oil has the lowest viscosity at 2.8 cSt.

2.6.3. Density

Density (defined as the mass per unit volume) of biodiesel increases with the increment of its molecular weight [12]. Among the seed oils, Castor seed oil has the highest density of 957 kg/m³, while Sugar apple has the lowest density of 817 kg/m³, which is lower than the density of diesel (830 kg/m³). Among the reported biodiesels, Neem biodiesel has the highest density (940 kg/m³), and both tKaranja and Rubber biodiesel have nearly the same density of 843 kg/m³.

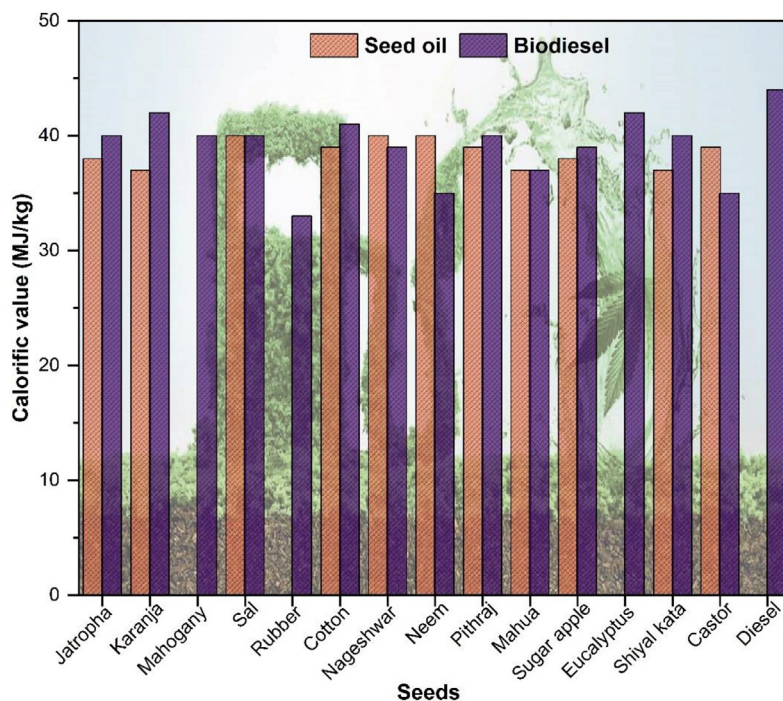


Fig. 7. Calorific Values of various non-edible seed oils, biodiesels produced from them and diesel [48,97–107].

Table 4

Fuel properties of various non-edible seed oil and their biodiesel resources.

Seed	Kinematic viscosity at 40 °C (cSt)		Density at 40 °C (kg/m ³)		Cetane number		Acid value (mg KOH/g)		Flash point (°C)		Cloud point (°C)		Pour point (°C)		References
	Seed oil	Biodiesel	Seed oil	Biodiesel	Seed oil	Biodiesel	Seed oil	Biodiesel	Seed oil	Biodiesel	Seed oil	Biodiesel	Seed oil	Biodiesel	
Jatropha	34	3.6	903	852	38	52	3.5	0.64	240	200	9		5	5	[13,15,108,109]
Karanja	40	4.9	924	843	42	54	5.4	0.42	225	130	3.5	14	-3	-3	[110–113]
Mahogany	35.6	3.1	926	880			11	0.49	165		7		9		[18,19,114]
Sal	61	4.8	870	857		53	66	0.18	238	160		6	-3.2	18	[4,6,20,73,115–118]
Rubber	32	5.1	915	843	46	76	4	0.12	294	120	0	3	-2		[119–121]
Cotton	29	6.1	900	874		53	0.08	0.12	255	200	0	-2	-2.3	5	[74,122–124]
Nageshwar	26.2	4.4	924	866		59	10	0.21	95	153	6	-4	-1.1		[33,125–127]
Neem	44	5.5	930	940	68	51	9.1	0.42	227	150	13	6	1		[75,128,129]
Pithraj	35	4.7	916	880	42	55	26.7	0.49	243	190	5	8	4	8	[50,76,130]
Mahua	24.1	4.1	917	852	57	60	3.55	0.39	231	130	14	3.5	12	-6	[53,131–133]
Sugar apple	42.6	5.3	817	870	48	57	0.85	0.40	235	160		5		3	[55,77,134,135]
Eucalyptus	3.8	2.8	903	888		55	2.1	0.25	116	105					[58]
Shiyal kata	35	5.1	905	868	51	53	4.7	0.34	220	130	12	9	-12	-15	[136–139]
Castor	107	15	957	897	40	56	2.4	0.21	294	169	14	-14		2	[140–142]
Diesel	4.1		830		50				75		-8.0		-7.5		[143,144]

2.6.4. Acid number

The acid number, defined as the required amount of KOH to neutralize the FFAs present in 1.0 g of oil, is a crucial parameter for selecting the appropriate method for biodiesel production. According to the AOAC 1980 method, the acid number for seed oil should be less than 4.0 mg KOH/g, while the European standard (EN 14104) and ASTM D664 accept a maximum value of 0.5 mg KOH/g for biodiesel. A higher acid content in oil can form soap during the base-catalyzed transesterification process. To prevent soap formation, acid-catalyzed esterification is necessary before the base-catalyzed transesterification process. Moreover, FFAs can cause corrosion in both the fuel supply system and the internal combustion engine. Among all the feedstocks, cotton seed oil meets the acid number range according to the European and ASTM standards. Sal seed oil has the highest acid number, which restricts its direct use in engines. Castor, Eucalyptus, Jatropha, and Mahua seeds oil show compatible acid numbers. Although FFAs cannot be completely removed in biodiesel, the acid values of all biodiesels fall below 0.64 mg KOH/g, with cotton seed oil having the lowest acid value in the biodiesel, as provided in Table 4.

2.6.5. Flash point, pour point and cloud point

The flash point indicates the lowest temperature at which a fuel emits enough vapor to ignite in the presence of a flame or a spark. Biodiesel has a high flash point (> 150 °C), resulting in an ignition delay, while the flash point of petrol and diesel is in the range of 55–66 °C. A higher flash point ensures enhanced safety during storage, handling and transportation of fuel. The pour point is defined as the temperature below which a fuel loses its flow characteristics. The pour points of seed oils and biodiesels are generally higher than those of conventional diesel. From Table 4, it can be observed that: (i) among the seeds oil, Shiyal kata and Mahua seed oils have the lowest (-12 °C) and the highest (12 °C) pour points, respectively, and (ii) among the produced biodiesels, Shiyal kata and Sal biodiesels have the lowest (-15 °C) and the highest (18 °C) pour points, respectively.

On the contrary, the cloud point of a fuel is the temperature at which it starts to form a cloudy and waxy appearance. These partially or fully solidified waxes thicken the fuel and can clog fuel filters and injectors in the engine. The cloud points of all available seed oils are much higher than that of commercial diesel, indicating that seed oils and the biodiesel derived from them perform poorly in engines at lower

Table 5
Comparison of engine performance (BSFC, kg/kW-h) of non-edible seed biodiesel blends with commercial diesel.

Biodiesel from	Engine type	Test condition	B0/D100	B05/D95	B10/D90	B20/D80	B30/D70	B40/D60	B50/D50	B60/D40	B100/D0	Ref.
Jatropha	4-stroke vertical compression ignition (CI) engine	Power: 7.4 kW, compression ratio: 16.5:1	0.261		0.265	0.267	0.269	0.270	0.286	–	0.321	[145]
Karanja	Single cylinder, 4-stroke,	Power: 4 kW, Compression ratio: 17.5:1,	0.2907	–	0.2821	0.3106	0.3137	–	0.3301	–	0.3655	[146]
Mahogany	Direct injection vertical CI engine	Power: 4 kW, Compression ratio: 17.5:1,	0.253	0.294	–	–	–	–	0.334	–	–	[147]
Sal	Single cylinder, water cooled diesel engine	Power: 3.5 kW, Speed: 1500 rpm	0.306		0.301	0.317	0.334	0.338				[148]
Rubber	Single-Cylinder CI engine	No load	1.1	–	0.5	0.58	–	–	–	–	–	[149]
Cotton	DI, Four Strokes, diesel engine	Torque 22 N-m, engine speed 850 rpm	0.34	–	0.34	0.35	0.37	–	–	–	–	[150]
Nageshwar	4-stroke direct injection CI engine	Power: 3.5 kW, Com. ratio: 17.5:1	0.27		0.32	0.28	0.31	–	–	–	–	[151]
Neem	4- strokes, Single-cylinder	BP 0.5Kw	0.95	–	0.81	0.815	0.98	–	–	–	–	[152]
Pithraj	Four-cylinder, IDI diesel engine	Compression ratio: 21:1,	0.353	0.356	0.359	–	–	–	–	–	–	[76]
Mahua	Single cylinder, Direct injection, CI engine	Compression ratio: 17.5:1, Speed: 1500 rpm	0.275		0.300	0.290	0.300	0.358				[153]
Sugar apple	Direct injection vertical CI engine	Power: 4 kW, Compression ratio: 17.5:1	0.335		0.344	0.325	0.342	–	0.339	–	0.331	[56]
Eucalyptus	Direct injection CI engine	Power: 4.8 kW, Speed: 1500 rpm	0.269		0.275	–	0.291	–	0.310	–	0.325	[57]
Shiyal kata	Single-cylinder, VCR engine	Compression ratio: 17.5:1,	–	–	–	0.31	–	0.33	–	0.39	0.41	[154]
Castor	Single cylinder, direct injection, CI engine	Load 0.87 kw	0.56	–	0.57	0.58	–	–	–	–	–	[155]

temperatures. Some biodiesels produced from different seed oils also have higher cloud points, except for Castor, Cotton, and Nageshwar biodiesels. The cloud points of Cotton and Nageshwar biodiesels are close to that of diesel. However, the cloud points for both seed oils and biodiesels are acceptable in the perspective of Bangladesh.

2.6.6. Cetane number

Cetane number (CN), which indicates the combustion speed of the fuel and the compression needed for ignition, is a primary property in determining the quality of diesel fuel. For a particular engine, a higher cetane number translates into a shorter ignition delay and thus can be effectively used in high speed engines. Biodiesels generally have high CNs because they contain long-chain fatty acids, esters, many of which are from saturated fatty acids found in seed oils. The CN of biodiesels can be measured using ASTM D613 and EN ISO 5165 test methods [12]. Table 4 shows that the CN for non-edible seed oils ranges from 38 to 68. Among all reported seed oils, Jatropha seed oil has the lowest CN (38), while the Neem seed oil has the highest value of CN (68). The produced biodiesels have comparatively higher CN (50 to 75.5) than the seed oils and even higher than commercial diesel (50), possibly due to the esterification reaction. Neem biodiesel has the lowest CN (51), whereas Rubber biodiesel has the highest CN (76), making it more suitable for high-speed diesel engines.

3. Combustion performance and emission characteristics of biodiesel from seed oils

The biodiesel produced from different sources is generally used in engines by blending with commercial diesel. The use of 100% biodiesel in the existing engines is not feasible as it requires some modifications

to commercial diesel engines. Hence, a blend of biodiesel with commercial diesel is advised by many researchers [156]. Brake Specific Fuel Consumption (BSFC), a measure of the fuel efficiency of internal combustion engines with a shaft output, is a key engine performance indicator. Furthermore, Brake Specific Energy Consumption (BSEC), which is the calorific value times BSFC, and Brake Thermal Efficiency (BTE), which indicates the ratio of the brake power obtained from the engine to the fuel energy supplied, are also measured to express engine performance. Table 5 illustrates the diesel engine performance in terms of BSFC when biodiesel is blended with commercial diesel and combusted in a diesel engine. Blends of biodiesel with commercial diesel containing 0%, 5%, 10%, and 20% of biodiesel are labeled as B0/D100, B05/D95, B10/D90, and B20/D80, respectively. The term B0/D100 indicates pure diesel (i.e., no biodiesel added), whereas B100/D0 means pure biodiesel (i.e., no commercial diesel added). Previous studies reported that a blend of up to 20% biodiesel with commercial diesel is possible with existing diesel IC engines, and further addition of biodiesel requires modification of the engines [157–159]. Barnitt et al. investigated durability of bus engines using 20% biodiesel blend for two years (100,000 miles) and found the engine and fuel system maintenance required was nearly identical for conventional diesel and the biodiesel blend [159].

Jatropha biodiesel demonstrated higher thermal efficiency and higher fuel consumption compared to commercial diesel. The blends of Jatropha biodiesel with diesel showed better brake power than commercial diesel. However, conditions such as the age of the engine can reduce BTE even when Jatropha biodiesel is blended. Karanja biodiesel blends, specifically B20D80 and B40D60, showed an average of 6% more torque, higher brake power, and better brake thermal efficiency compared to diesel fuel. Additionally, a 3% lower brake specific fuel consumption was attained when running a diesel engine under

similar conditions [148,160]. No report on the engine performance and emission characteristics of the Mahogany biodiesel from Bangladesh has been published yet.

The use of sal biodiesel in a direct injection diesel engine showed performance nearly identical to diesel in terms of BSFC, and BSEC, but with a slightly lower BTE [91]. Sal biodiesel blends (10% and 20%) in a diesel engine resulted in an increase in BTE value by 2.3% and 2.4%, and reductions in BSEC by about 1.84% and 2.09%, respectively, compared to mineral diesel [161]. Hence, Sal biodiesel can be used directly or blended with commercial diesel in existing diesel engines without requiring engine modifications. In contrast, using rubber seed biodiesel in a diesel engine increased the BSFC value [12], which is often associated with a low heating value and high viscosity of the fuel [72]. However, the BTE value increased by 1.1–1.3% with higher biodiesel content in the blend [12], and it also increased engine speed and power.

For cotton seed biodiesel, a lower blend results in about 6% in BTE, while BSFC decreases [12]. On the contrary, BSFC is inversely proportional to BTE [124]. Nageshwar biodiesel exhibits lower BTE and BSFC compared to conventional diesel. Neem biodiesel demonstrates reduced thermal efficiency and poorer combustion properties due to its high viscosity [25]. However, biodiesel blends of Neem, such as B10D90 and B20D80, show brake thermal efficiency like that of fossil diesel. Neem biodiesel has higher BSFC compared to fossil diesel, though BSFC decreases at an 8.25% load condition [25].

Pithraj biodiesel blends B5D95 and B10D90 reduced the brake torque by 0.9% and 1.8%, respectively, increased the brake specific fuel consumption by 0.87% and 1.78%, respectively, and decreased brake power by 0.9% and 2.1%, respectively [76]. These blends show lower engine thermal efficiency compared to diesel fuel owing to their lower energy content, higher viscosity, and greater density [50]. Mahua oil biodiesel, with a high density (883 kg/m³) and poor volatility compared to commercial diesel, leads to more fuel inlet and a lower combustion rate, resulting in decreased thermal efficiency. However, Manhua oil also reduces CO, UHC, smoke and NO_x emissions [162]. Increased specific fuel consumption due to the higher density and lower heating value of biodiesel results in partial combustion. Despite lower brake thermal power and higher smoke intensity at higher biodiesel concentrations, the B20 blend is promising for unmodified diesel engines due to its comparable thermal brake power and lower smoke emission relative to diesel [163].

The biodiesel blends from Sugar apple, specifically B20D80 and B30D70, showed higher brake thermal efficiency and lower CO, CO₂ and HC emissions, indicating their potential to replace conventional diesel [164]. Generally, brake thermal efficiency decreased and brake specific fuel consumption increased with higher biodiesel blend volumes. Among Eucalyptus biodiesel blends, B10 is found to be the most suitable, as its BSFC is nearly equal to diesel, and its BTE is slightly lower. For Shiyal kata seed biodiesel, BSFC decreases with the increase in load, while BTE increases with higher biodiesel blend ratios up to 30%, except at high speeds (3500–4000) and lower loads [139]. Castor oil biodiesel blends with diesel resulted in increased BSFC and BTE [155].

Emissions from biodiesel and its blends with commercial diesel are crucial for evaluating their viability in engines. For diesel fuel in a four-stroke single-cylinder engine, average emissions are approximately 915 g/KW-h for CO₂, 0.072% for CO, 19 ppm for hydrocarbons, and 984 ppm for NO_x, and 43% for smoke [165,166]. Biodiesel combustion generally decreases CO, particulate matter, hydrocarbons and smoke but increases CO₂, and NO_x emissions compared to diesel, due to the higher oxygen content in biodiesels [147,161]. Jatropha and Karanja biodiesels show reduced CO emissions compared to conventional diesel, through NO_x emissions increase when blended with commercial diesel [167]. Karanja biodiesel, specifically, can reduce smoke and CO emissions by 43% and 50%, respectively, while NO_x emissions increase by 15% [111]. Similarly, Sal biodiesel reduces CO,

HC, and NO_x emissions by 45%, 55% and 12%, respectively, compared to diesel, though CO₂ emissions increase due to enhanced combustion in the presence of O₂ [91]. Biodiesel blends typically reduce CO and HC significantly; however, NO_x emissions increase for all blends due to higher combustion temperature and excess availability of oxygen [161].

In the case of Mahogany biodiesel from the Philippines, B50/D50 blends emitted less CO₂, CO and HCs [147]. Rubber seed biodiesel has lower emissions of HCs, CO (decreased by 0.13–1.13%), NO_x, and smoke opacity (by 37.03%) under low load conditions at high biodiesel concentrations in the blend [12]. AB30/D70 blend of Cotton seed biodiesel showed a 24% reduction in CO emissions during combustion, although NO_x emissions increased by 10%. Additionally, B10/D90 and B20/D80 biodiesel blends demonstrated a reduction of particulate matter (by 24%) and smoke (by 14%) emissions [124].

Biodiesel blend of Nageshwar, B20/D80, showed decreased emission of CO, HC and smoke opacity by 57.9%, 28.8% and 4.2%, respectively, while CO₂ and NO_x increased by 8.97% and 34.05%, respectively. Thus, making it an easy decision to use B20/D80 in the engine without any amendment [151]. Biodiesel from Neem seed oil also showed reduced emission of CO, HC, NO_x and smoke [152].

In the case of biodiesel from Pithraj seed oil, the emissions of NO were found to increase by 2.2% and 7.3%, and emissions of CO₂ increased by 4.41% and 6.21% in B05/D95 and B10/D90 blends, respectively [76]. In contrast, these blends decreased HC emissions by 9.9% and 22.3%, respectively, and CO emissions by an average of 4.7% [76]. It is also reported that Pithraj biodiesel blends result in lower smoke emission and engine noise compared to diesel fuel [50].

Though Mohua biodiesel requires higher fuel intake in a diesel engine, it lowers emissions of CO, UHC, NO_x and smoke intensity, making Mahua biodiesel a prominent green fuel [168]. Sugar apple biodiesel blends perform similarly to conventional diesel with lower exhaust emissions such as CO, CO₂, and HC, with the B20 blend being the most suitable for replacing conventional diesel [169]. Eucalyptus biodiesel emits less smoke and is more environmentally friendly than commercial diesel [57]. Biodiesel from Shiyal kata and Castor oil emits higher amounts of NO_x and CO₂ when blended with commercial diesel, whereas HC, CO and smoke emissions reduce with increasing percentages of biodiesel blends and compression ratio [139,170].

Overall, using non-edible seed biodiesel shows some general trend in engine performance and emissions characteristics. The brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emission of Nitrogen oxides (NO_x) and Carbon dioxide (CO₂) are slightly increased in up to B20 compared to conventional diesel (Table 5). On the other hand, biodiesel blends noticeably reduce the emission of carbon monoxide (CO), hydrocarbons (HC), and smoke owing to the higher fuel oxygen content, which promotes combustion [161,164]. For example, Karanja biodiesel blends (B20) demonstrated higher brake power and thermal efficiency, with a slight increase in BSFC long with reduced CO and smoke by up to 50% and 43% [111,160]. Likewise, Sal biodiesel blends maintain similar BSFC to diesel and slightly improved BTE, and also diminish CO and HC by 45%–55% [91]. Therefore, using up to B20 biodiesel blend is recommended, as they provide an effective balance between maintaining engine performance close to conventional diesel while lowering CO, HC, and smoke emission significantly, albeit with slightly higher NO_x and CO₂ emissions.

4. Other biofuels from selected non-edible resources

4.1. Bio-oil

Bio-oil, another liquid form of biofuel, is gaining popularity in recent years. This oil, also known as pyro-oil, can be obtained mostly by pyrolysis at a temperature range of 350–650 °C in the absence of air. It can be produced from various raw materials such as Municipal Solid Wastes (MSW), seed oil, seed cakes after oil extraction, waste tires

and tubes, via pyrolysis. The produced bio-oil can be used directly as furnace oil, in burners, and in the preparation of mosquito killing coils. For use as petro-fuel in commercial engines, further modifications such as thermal or catalytic cracking, reforming, and other processes are necessary. Bio-oil yield can be increased by co-pyrolysis with waste polystyrene [171]. Pyrolysis of *Jatropha* seed cake yields more than 50% bio-oil [172], *Karanja* seed gives 57–65.6% [173], *Mahogany* seed oil yields 49%–50% [174], and *Sal* seed yields 52.8 wt% [175]. Bio-oil yield is 22.0% from rubber seed cake, 32% from cotton seed during catalytic (Zeolite) pyrolysis [176], and 52 wt% from *Shiyal kata* seed pyrolysis [177].

4.2. Biochar

Biochar, a high carbon, fine-grained residue, is obtained during pyrolysis. It can be derived from organic feedstock such as agricultural wastes and municipal solid waste (sludge) [178]. Biochar has a wide range of uses, including heat and electricity generation, flue gas cleaning, metallurgical applications, agricultural and animal husbandry, water purification, construction material, and medicinal applications [179]. It also improves soil fertility and aids in carbon sequestration [179]. During direct gas-fired pilot-scaled pyrolysis of *Jatropha* seed cake at 500 °C, approximately 28%–30% biochar was generated, which has high potential as an adsorbent for the removal of different pollutants [180]. Slow pyrolysis in a fixed bed reactor at 550 °C produced around 33–36 wt% biochar, usable as solid fuel in boilers or as feedstock for activated carbon [181,182]. The pyrolysis of *Karanja* seed cake yields around 28%–30% biochar [180]. The solid residue after pyrolysis of *Sal* seed showed a dramatic increase in fixed carbon content (53.4%) compared to raw *Sal* seed (16%), due to reduced oxygen to 7.74%, with no moisture content and a gross calorific value of 24.96 MJ/kg, higher than *Sal* seed [175]. Activated carbon from *Eucalyptus* seed showed outstanding adsorption capacities for pollutants phenol, 4-chlorophenol, and 4-nitrophenol, at 2.12 mmol/g, 2.57 mmol/g and 3.89 mmol/g, respectively [174].

4.3. Bioethanol

Bioethanol, a renewable biofuel and alternative to fossil transportation fuel, can also be produced from seed oil and seed cakes. This bioethanol can be derived from several types of feedstocks such as corn, non-edible seeds, soybeans, wheat straw, woodchips and recently, microalgae via fermentation processes. With its high-octane rating, bioethanol can be directly used in transport vehicles and has the potential to reduce automobile emissions. Polysaccharides in *Jatropha* seed cake can be transformed into bioethanol by sequential hydrolytic and fermentative processes [183]. Residual wastes of *Karanja* oil seed, including hull and kernels, can also be used for bioethanol production [184]. Furthermore, bioethanol can be produced from *Sal* seed using a *Zymomonas* Specific Medium (ZSM) catalyst [185], from *Mahua* flower [186], and from *Castor* stems, seed cakes and leaves through saccharification and fermentation processes [142].

4.4. Biogas

Biogas, a gaseous fuel produced by anaerobic digestion, can also be obtained from non-edible seed cakes. Anaerobic digestion of a slurry made from *Jatropha* seed cake in a ratio of 1:20 with water generated 1 m³ pure methane from 6.4 kg of seed cake over 60 days [187]. A mixture of *Karanja* seed cake and cow dung in a 1:3 ratio can produce biogas containing 73% methane, and 17% CO₂, with a heating value of 27.5 MJ/Kg, and about 6–6.5 kW/m³ energy content [188]. Mixing rubber seed cake with cow dung and 2% TiO₂ results in maximum biogas production, which contains 28% methane at 40 °C [189]. Furthermore, biogas production from cotton seed hull and oil cake [190], a mixture of sesame and neem cake

(50:50 waste/waste) [191], *Mahua* pressed seed cake [192], *Shiyal kata* (*Argemone Mexicana*) seed waste [60], *Castor* stem, seed cake, and leaves [142] through anaerobic digestion has been reported in various studies.

5. Challenges and possible solutions for future biodiesel production in Bangladesh

5.1. Production cost

Although biodiesel is a fuel obtained from renewable sources, unlike the non-renewable and limited fossil fuels, its production costs are higher due to the nature of the raw materials and the technologies involved. Currently, biofuels contribute about 0.8% of total global energy consumption in transportation [193]. However, from the perspective of transport fuel, it was reported in 2017 that the production cost of biodiesel (0.8–0.83 USD/L) is higher than that of gasoline (0.43–0.46 USD/L) and diesel (0.42–0.47 USD/L) [194]. While biodiesel offers long-term benefits, developing countries like Bangladesh may find it a more expensive alternative that is harder to accept. The government can subsidize future industries producing biodiesel to make it less expensive and more accessible to the populace.

5.2. Biofuel policy

Fossil fuels contribute almost 85% of total global fuel consumption. These non-renewable resources are major contributors to global warming. With the rapid exhaustion of fossil fuel, biofuels such as biodiesel, bioethanol, biohydrogen and biogas have been introduced to meet future energy demands. However, the biodiesel industry's infrastructure and financial profitability are still underdeveloped compared to the fossil fuel industry. Therefore, a biofuel policy pertaining biodiesel production industry must focus on providing the necessary support and encouraging private investment through various schemes is inevitable. Strong governmental support and a robust biofuel policy are crucial for the success of the biofuel industry. It is also necessary to set targets and parameters for biofuel production, technologies, export–import tariffs, and resources creation. Different countries adopted specific policy recommendations to ensure the continuous and sustainable development and execution of biofuel initiatives.

Brazil was the first country to adopt a policy on biofuel, focusing on bioethanol from sugarcane to reduce fossil fuel dependency. Brazil uses both hydrous E100 and ethanol blends in car engines and aims to achieve a target of using anhydrous-E27 ethanol blends. Additionally, Brazil currently uses B10D90 biodiesel blends and plans to increase this to B15D85 by 2025 [193]. In contrast, India's Revised Policy on Biofuels targets 20% ethanol blends in petrol and 5% biodiesel in diesel by 2030 [193]. India permits the import of biodiesel feedstocks and direct foreign investment up to 100% in biofuel technologies but has banned biodiesel imports. Currently, biofuel contributes 1.2% to transport sector in India, and fuel excise or tax reductions are not authorized yet [195]. The National Policy on Biofuels 2018 aims to reduce energy emission intensity by 33%–35% by 2030 [196].

Following the strategic policies of Brazil, India and other countries, Bangladesh should adopt a biofuel policy to address its energy needs through renewable sources. In 2018, the Government of Bangladesh allowed a 5% bioethanol blend with octane and gasoline [197]. However, there is currently no policy regarding biodiesel. Given Bangladesh's significant potential for growing oil-bearing crops, adapting a suitable policy could enable the country to commence commercial biodiesel production and set a goal of incorporating 5% biodiesel in blends by 2030.

5.3. Raw material supply

Biodiesel production industries may face challenges in getting a sufficient supply of raw materials due to various obstacles. For instance, non-edible seed trees, often require specific weather, agricultural and geographical conditions to grow and yield a good harvest. Failure to meet these conditions can result in inadequate production of non-edible seed oil, which is the main feedstock for biodiesel. To address these issues, the government should provide proper support for the cultivation of non-edible seeds and other biodiesel feedstocks and consider reducing taxes on imported materials essential for biodiesel production.

5.4. Scientific and technological barriers

In a developing country like Bangladesh, scientific and technological development is still challenging. To foster the growth of biodiesel, as a greener source of energy, there is a need to focus on R&D, pilot-scale trials, and commercial-scale production, along with efforts to improve biodiesel quality. Encouraging further exploration of biodiesel technologies, along with supporting training programs in universities, research institutes, and relevant organizations, is important for the advancement of this sector.

5.5. Public support

Support and awareness are crucial for the future of biodiesel production. Currently, most of the population remains unaware of the harmful effects of fossil fuels and the benefits of biodiesel. Furthermore, the higher cost of biodiesel contributes to a negative perception among the public. To address this, increasing public awareness about the harmful impacts of fossil fuels and the advantages of biodiesel is essential. Conducting seminars, workshops, discussions, public speeches, and media campaigns through mass media and the internet can help to educate the public and gain public support.

6. Conclusion

Biodiesel presents a good alternative to petroleum diesel that offers benefits such as environmental protection, reduced dependence on crude oil, engine compatibility, economic growth, and job creation. For Bangladesh to realize these advantages, it should develop and adopt a tailored policy. The proper utilization of non-edible seeds to value added products like biodiesel and its blend with commercial diesel could significantly transform the energy sector. The review suggests that biodiesel from *Jatropha*, *Karanja*, *Eucalyptus*, and *Rubber* seeds are promising for both commercial production and environmental point of view. Compulsory mixing of biofuels with the fossil fuels can accelerate this transformation. However, further research is needed to address technology development, operational scaling, continuous supply of raw materials, and feedstock costs to ensure efficient biodiesel production.

CRedit authorship contribution statement

Ehsanul Hoque: Writing – original draft, Visualization, Conceptualization. **Md Ismail Hossen Emon:** Writing – review & editing, Writing – original draft, Methodology. **Md Tawfiq Anik:** Visualization, Methodology. **Mohammad Ariful Islam:** Writing – original draft, Data curation. **Ikramul Hasan:** Writing – review & editing, Conceptualization. **Tanvir Ahmed:** Writing – review & editing, Writing – original draft. **Zia Ullah Arif:** Writing – review & editing, Writing – original draft. **Mokarram Hossain:** Writing – review & editing, Conceptualization. **Mohammad Ismail:** Writing – review & editing, Supervision, Conceptualization.

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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