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Liquid Biofuels Production and Emissions Performance in Gas Turbines: A Review

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Abstract

The increasing demand for clean and sustainable energy sources provides the impetus for the development of alternative fuels. Recent development of fuel-flexible gas turbine technologies enables the use of alternative non-fossil fuels that could play key roles in contributing to the global efforts in meeting emissions targets. This review highlights the current state-of-the-art production and properties of alternative fuels such as straight vegetable oil (SVO), biodiesel, bioethanol, bio-oil, hydrogenated vegetable oil (HVO) and Fischer-Tropsch (FT) fuel. This is followed by the evaluation of combustion performances in gas turbines. All of the alternative liquid biofuels have shown their potentials in reduce regulated emissions such as NO_x, CO and soot under favourable operating conditions. Both HVO and FT fuels show comparable performance as that of jet fuel and can be used in aviation gas turbines, although the present day high production cost restricts the large-scale adoption, limiting its utility. They also have considerably higher cetane number than the rest, making it easier for the fuel to ignite. As for stationary power generation gas turbines that need not carry payloads, the other four alternative biofuels of biodiesel, bioethanol, bio-oil and SVO are possible candidates despite the physics-chemical properties variations when compared to fossil fuels. Amongst them, the use of SVO and bio-oil in gas turbines would require the parallel development of fuel supply systems and atomisation technologies to improve the combustion of the fuels. In all, the alternative liquid fuels reviewed provides realistic opportunities for cleaner and more sustainable operation of aviation and power generation gas turbines. Profound understanding on the fundamental combustion characteristics of the fuels are essential to expedite their mass adoption in gas turbine applications.

Keywords: gas turbine; biofuels; alternative fuel; jet fuel; biodiesel; FT fuel

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85 **1.0 Introduction**

86 Biomass-derived alternative fuels produced from renewable biomass are important
87 owing to them being potentially carbon neutral, producing cleaner combustion and having
88 sustainable feedstock supply from existing plantations [1]. From a carbon cycle perspective,
89 carbon dioxide (CO₂) produced from the combustion of fossil fuels are discharged into
90 atmosphere without recycling, whereas biofuels are potentially carbon neutral as the CO₂
91 produced from the combustion process is reabsorbed for feedstock plant growth. Fig. 1
92 compares the CO₂ emission cycle between fossil fuels and biofuels.

93 At present, the usage of biofuels is not yet prevalent despite the positive benefits to the
94 environment. This is due to the high cost associated with biofuels production and the relatively
95 lower crude oil price in recent years. These form the primary reasons for the continued reliance
96 on fossil fuels for power generation. Fig. 2 shows the price comparison of fossil fuel-based
97 compressed natural gas (CNG) and diesel with biofuels, i.e. biodiesel (B99/B100) and
98 bioethanol (E85) since the turn of the millennium [2]. As expected, fossil diesel is consistently
99 cheaper than biodiesel and bioethanol. CNG is relatively cheaper than all of the liquid fuels
100 compared and hovers around US\$2 per gasoline-gallon equivalent (GGE) over the past few
101 years. However, the need for high pressurisation and the low energy density of CNG renders it
102 to be less practical as compared to liquid fuel in terms of storage and the inherent power
103 contained.

104 The US Energy Information Administration reported that only 10% of total energy
105 produced came from renewable sources in 2016, out of which, about 22% was contributed by
106 biofuels [3]. There have been calls to table climate change policies to limit the consumption of
107 fossil fuels in order to reduce the gap between fossil fuels and alternative energy sources [4,5].
108 In December 2015, 195 countries agreed to a global climate deal during the UN Climate
109 Change Conference in Paris (COP21) to pledge the reduction of greenhouse gases in order to

110 achieve a global temperature rise of below 2 °C above pre-industrial levels [6]. Despite the
111 announcement of the US about their withdrawal from the 2015 Paris agreement in June 2017,
112 global efforts on reducing greenhouse gas emissions continue to gain momentum for most
113 countries [7]. One way to achieve the goal of greenhouse gas emissions reduction is by adopting
114 renewable energy sources [6]. The political will and investment committed in sustainable
115 energy technology catalyst have spurred the production of biofuels, which could subsequently
116 lead to reduction of production cost through economies of scale [8].

117 Gas turbine is one of the power generation systems that contribute to the global
118 greenhouse gases emissions. The technology of gas turbine started exclusively for the aviation
119 industry in the 1960s but rapidly progressed to become an important power generation system.
120 A key milestone that led to gas turbine's rise as a prominent mode of power generation is the
121 development of combined cycle power plants that incorporates the combination of gas and
122 steam turbines, allowing the energy conversion efficiency to be boosted up to around 60%
123 [9,10]. Additionally, most of the combined cycle power plant are fuelled by natural gas, which
124 makes it cleaner than coal-powered power plants [9].

125 The capacity factor for natural gas powered combined cycle plants between year 2005
126 and 2015 in the U.S is shown in Fig. 3. The capacity factor increased from an average of 35%
127 in 2005 to 56% in 2015 [11] owing to increasing demand. The increase in usage capacity
128 signifies the inevitable increase of greenhouse gases production, i.e., CO₂. In order to meet the
129 increasingly stringent environmental legislations and emissions targets, recent research has
130 focused on the development of clean, sustainable biofuels and low emission technologies. In
131 the field of gas turbines, fuel-flexibility technology is desirable from the standpoint of meeting
132 emissions goals and reducing operating costs [12,13]. Potential biomass-derived liquid fuels
133 that have been identified as substitute for conventional fuels or supplemental fuels include
134 straight vegetable oil (SVO), biodiesel, hydrogenated vegetable oil (HVO), bioethanol, bio-oil

135 and Fischer-Tropsch (FT) fuel. This paper critically reviews the production process of liquid
136 biofuels, fuel properties and previous studies related to the performance and combustion
137 characteristics under gas turbine operating conditions.

138

139 **2.0 Applications of liquid biofuels in gas turbines**

140 Gas turbine is a power generation system that is known to be fuel-robust and able to
141 accommodate different types of fuels. To substitute fossil-based fuels, biomass-derived
142 alternative fuels are attractive options that have gained much interest in recent years in view of
143 their renewability and potentially lower emissions. The development of different techniques
144 and production processes that convert biomass into bioresource energy in recent decade have
145 been rapid. The production pathways of the main liquid biofuels are shown in Fig. 4. In general,
146 straight vegetable oil (SVO) is produced directly from mechanical, chemical and enzymatic
147 extraction methods. Biodiesel is produced via the process of transesterification of vegetable oil.
148 Hydrogenated vegetable oil is produced from SVO and animal fats that undergo hydrogenation
149 and isomerisation processes. By pyrolysing biomass, bio-oil and synthesis gas can be produced.
150 The synthesis gas that contains H_2 and CO derived from pyrolysis and gasification processes
151 can be used to produce Fischer-Tropsch (FT) fuel. Bioethanol is produced from biomass via
152 hydrolysis and fermentation processes. The variety of feedstock and production methods used
153 to produce the biofuels result in significant differences in the physical and chemical properties,
154 which subsequently affects the combustion quality and performance in gas turbines. Thus,
155 understanding the physical, chemical and rheology properties of the fuels is essential to ensure
156 system safety, design of fuel-flexible combustor and optimise the performance of existing gas
157 turbine systems. The following sections review in detail the physio-chemical properties,
158 production methods and combustion performance characteristics of each type of biofuels.

159

160 **2.1 Straight vegetable oil (SVO)**

161 **2.1.1 Properties of SVO**

162 Vegetable oil can be used directly as fuel in gas turbines [14,15] and internal
163 combustion engines [16,17]. SVO consists of triglycerides that contain three molecules of fatty
164 acids and one molecule of glycerol [18]. The positive attributes of SVO as alternative fuel are
165 biodegradable, renewable and low sulphur and aromatic content [19]. The viscosity for SVO
166 is about an order of magnitude higher than that of diesel, highlighting the major drawback of
167 SVO in gas turbine application, as shown in Fig. 5. High viscosity of SVO results in inferior
168 atomisation, increases carbon deposition and subsequently reduces combustion efficiency
169 [20,21]. One way to reduce the viscosity of SVO is by preheating the fuel and blend with
170 conventional diesel. Despite the feasible usage of SVO in engines, previous experimental
171 works have shown that the tendency of soot deposition increases with the proportion of SVO
172 in fuel [20,21]. Carbon deposition in the combustion chamber and injection system undesirably
173 shortens the life span of the engine, leading to the increase in maintenance cost [22]. Cetane
174 number is a measure of autoignition quality of a fuel. A fuel that is easier to ignite has higher
175 cetane number. The degree of unsaturation in SVO affects the cetane number. Overall, SVO
176 contains lower cetane number compared to conventional diesel or Jet A-1 as shown in Fig. 5,
177 indicating that SVO is harder to ignite when used as operating fuel. Despite the difference in
178 chemical composition as compared to fossil diesel, the calorific value for SVO (38 MJ/kg) is
179 only marginally lower than that of fossil diesel (42.5 MJ/kg), as indicated in Fig. 5. The
180 calorific value for SVO is lower than fossil diesel by approximately 11% due to the presence
181 of oxygen.

182 SVO can be derived from a variety of plants such as palm, jatropha, castor, jojoba,
183 karanja, tobacco, rapeseed, sunflower, soybean, candlenut and chestnut. The oil content for
184 these plants typically range from 20-60 % wt [18]. The physical properties of these feedstocks

185 are shown in Table 1. The SVOs from rapeseed, sunflower, palm, peanut and sesame are
186 slightly more viscous ($>35 \text{ mm}^2/\text{s}$) compared to jatropha, soybean, safflower, and coconut (<35
187 mm^2/s). Castor SVO has a relatively high viscosity of $250 \text{ mm}^2/\text{s}$, which is nearly one order of
188 magnitude higher as compared to other feedstock, making it not ideal for the fuel delivery and
189 injection system. The primary constituents of SVO, fatty acid, can be categorised into saturated
190 and unsaturated types. Saturated-chain fatty acid contains no double bonds between the carbons;
191 while unsaturated chain contains double bonds [23]. The degree of unsaturation is one of the
192 main factors that affect the overall physical properties of SVO [19,24]. In general, higher
193 degree of unsaturation (more double bonds in the chain) leads to lower viscosity of the oil
194 [24,25]. This is due to the existence of double bonds in the fatty acid bending the chains,
195 resulting in the existence in liquid form with lower viscosity [24,25]. On the other hand,
196 feedstocks with lower unsaturation degree, such as those of palm and coconut oil tend to have
197 higher cetane number (40-42) when compared with other feedstock [24]. The variation of
198 SVO's calorific value is correlated to the degree of unsaturation, where feedstock with higher
199 unsaturation degree such as soybean, corn, rapeseed and safflower possess higher calorific
200 value ($>39.4 \text{ MJ/kg}$) against those with lower unsaturation degree such as coconut, jatropha
201 and peanut ($<38 \text{ MJ/kg}$). SVO with higher degree of unsaturation has higher C/H ratio which
202 results in the elevated calorific values. The density for SVO is generally higher than that of
203 diesel owing to the higher molecular weight of the former. Table 1 shows that SVO density
204 can be correlated to the degree of unsaturation, where SVO with higher unsaturation degree
205 (>1.3) has density below 915 kg/m^3 than those with lower unsaturation degree (<1.3) such as
206 palm and coconut ($> 915 \text{ kg/m}^3$).

207

208 **2.1.2 Production of SVO**

209 The production process of SVO generally consists of five stages: (i) seed storage, (ii)
210 pre-treatment, (iii) oil extraction, (iv) filtration, and (v) storage [19]. As shown in Fig. 4, the
211 methods used to extract oil from seeds or kernels of plants can be categorised as mechanical,
212 chemical and biological extraction [18]. Under mechanical extraction, pressers are used to
213 extract oil. The pressers can be of ram or screw type. Screw presser is able to extract up to 95%
214 of oil from feedstock, while ram presser can extract about 65% of oil from feedstock [18,38].
215 Chemical extraction utilises solvents such as *n-hexane*, bioethanol or isopropyl alcohol for oil
216 extraction [38]. The overall efficiency of the process is governed by the types of solvent used,
217 pH level, particle size, agitation process and operating temperature [18,38]. A major
218 disadvantage of chemical extraction is the generation of hazardous waste water that is
219 detrimental to the environment and human health if left untreated [18,38]. For biological
220 extraction, enzyme such as alkaline protease is used to extract oil from crushed seed. This
221 method is environmental friendly, but the downside is long processing time (6 hours) and low
222 yield (38%) [18]. Post-extraction treatment is needed for all extraction method as the extracted
223 oil typically contains contaminants and is sticky. Filtration and purification processes are
224 applied to remove solid impurities, degum the sticky oil and neutralise the oil by adding alkali
225 such as sodium hydroxide [19].

226

227 **2.1.3 Performance of SVO in gas turbines**

228 Direct application of SVO in gas turbine is an attractive option as low cost is incurred
229 from oil processing. However, the viscosity of SVO is an order of magnitude higher than
230 conventional fossil diesel, posing a technical challenge when applied in gas turbine system as
231 highly viscous oil will negatively impact fuel flow delivery and result in inferior spray
232 atomisation process. Some practical steps have been undertaken to overcome the physical
233 properties challenge, including modifying the fuel delivery system by adding fuel preheating

234 capability and using twin-fluid injector that allows variation of the controlling parameters.
235 Blending SVO with conventional fuel is another strategy to maintain low viscosity of the
236 blended fuel. The performances of SVO as a viable gas turbine fuel have been tested by
237 different groups, as shown in Table 2 where the feedstock and control parameters are
238 summarised.

239 Varying the atomising air-to-liquid ratio (ALR) in a twin-fluid atomiser is an effective
240 control parameter to atomise SVO. Niguse and Agrawal [39] reported a reduction of NO_x level
241 by a factor of 4 when the ALR was increased from 2.0 to 3.0 in a swirl burner operated with
242 SVO, but the CO emission was not obvious when compared with baseline diesel. In a lab-scale
243 lean premixing and prevaporising (LPP) burner, Kun-Balog and Sztanko [40] reported a
244 reduction of CO and UHC emissions by more than 50% when atomising rapeseed oil at higher
245 atomising air pressure. Jozsa and Kun-Balog [41] further identified that SVO has poorer
246 stability limit than diesel under LPP burning conditions, particularly at low atomising air
247 pressure. Further increase of atomising air pressure led to increased flame stability with lower
248 CO, while the NO_x emissions for rapeseed oil were found to be lower as compared to baseline
249 diesel. Hashimoto et al. [42] utilised a gas turbine burner with twin-fluid atomiser to examine
250 the combustion characteristics of jatropha oil. Result showed that NO_x emissions for both diesel
251 and jatropha oil were around 50 ppm and decreased monotonically with the increase of air flow
252 rate.

253 The increase of ALR led to higher air momentum to effectively disintegrate the viscous
254 fuel into fine droplets for vaporisation. If insufficient atomising air was imparted, inferior
255 atomisation of SVO causes large droplets to move towards the combustor wall, causing lower
256 burning temperature and incomplete combustion that subsequently leads to higher CO
257 emissions. The SVO spray flame appearances varied with ALRs. At ALR < 2, yellow sooty
258 spray flame was established, indicating a poor fuel-air mixing with high level of soot

259 production. Increasing the ALR to beyond 2 resulted in an improved mixing of fine droplets
260 and air, creating flames that were bluish and analogous to a well-premixed flame [39].

261 As fuel viscosity is inversely proportionate with temperature, preheating the SVO is an
262 effective method to reduce the viscosity to the level of conventional fossil fuel. Sallevelt et al.
263 [43] raised the fuel injection temperature in a series of MGT tests. The SVO's viscosity was
264 reduced significantly by a factor of 3, leading to improved combustion efficiency with 28% of
265 lower carbon monoxide (CO) emissions. Likewise, Chiaramonti et al. [44] managed to achieve
266 CO reduction by 40% relative to biodiesel when combusting preheated rapeseed SVO (120 °C)
267 in an MGT (Garrett GTP 30-67) [44]. Prussi et al. [14] reported that the effect of preheating of
268 SVO on emissions was significant, where CO was seen to reduce by 28% in an 18 kW micro
269 gas turbine when preheating SVO to 120 °C. Preheating the SVO enables direct application in
270 gas turbine with positive effects on emissions.

271 There were some attempts to blend SVO in small quantity with fossil fuel, thus
272 removing the need of preheating. Panchasara et al. [45] tested the blends of 10-30% vol.
273 soybean oil with diesel using a gas turbine type burner. The CO emissions for the SVO/diesel
274 blends were reported to increase by 15% as compared to baseline diesel fuel under constant
275 fuel flow rate. The effects of using different SVO feedstock blends on the emissions were
276 studied by Chiariello et al. [15] in a micro gas turbine system. Two types of oils were used,
277 namely sunflower and rapeseed, under partial and full load micro gas turbine conditions. Result
278 showed that sunflower oil exhibited higher propensity of soot formation compared to rapeseed
279 oil blend by a factor of 16.7, owing to the high content of linoleic acid in the former that
280 promotes for the formation of ethene and ethyne during thermal decomposition which are
281 known to be soot precursor [46]. These results show that SVO blends lower soot emissions,
282 although CO was seen to increase. The inherent difference in SVO composition depending on
283 feedstock is another factor that affects emissions.

284 Despite the high CO emissions, the wide availability, ease of storage, near zero toxicity
285 makes SVO an attractive fuel for micro gas turbines. The issue of high viscosity can be
286 overcome by utilising a twin-fluid atomiser with high ALR and preheating the SVO. Moreover,
287 recent study has shown that using superheated steam as atomising fluid is another possible
288 method of reducing the CO, NO and UHC [40]. These strategies show that SVO can be a
289 potential fuel for micro gas turbine, provided modification to the fuel delivery system and
290 injector system is made to accommodate the high viscosity, and the controlling parameter is
291 optimised to achieve low emissions.

292

293 **2.2 Biodiesel**

294 **2.2.1 Properties of biodiesel**

295 The use of SVO in gas turbine has been associated with many problems, mainly
296 attributed to its high viscosity, low volatility and low cetane number. The SVO can further be
297 processed into biodiesel with properties that meet the European Union and U.S standards.
298 Biodiesel is oxygenated, renewable, biodegradable and inherently contains low level of sulphur
299 [47]. Regardless of feedstock, sulphur content in all biodiesel is below 0.01 % wt, which is
300 lower than standards set by European Union (max 0.02 % wt) and U.S. ASTM (max 0.05 % wt),
301 as shown in Table 3. However, the high viscosity of castor biodiesel does not conform to both
302 EU and US standards. The physical properties of biodiesel are similar to that of diesel in terms
303 of calorific value, viscosity, cetane number and density as shown in Fig. 5. Biodiesel can be
304 used as fuel directly or blended with fossil diesel in engines [48,49]. Table 3 compares the
305 properties of biodiesel from different feedstock against standards.

306 The properties of biodiesel is influenced by the degree of unsaturation of the molecules
307 [24,51]. Table 3 shows that feedstock with low degree of unsaturation (0.62-1.15) such as palm
308 oil and jatropha produce biodiesel with poorer cold flow properties (pour point ≥ 0 °C).

309 Although better cold flow properties were obtained for biodiesels with higher degree of
310 unsaturation (> 1.3) such as rapeseed, soybean, and sunflower, they are still considered inferior
311 when compared with diesel ($-21\text{ }^{\circ}\text{C}$) or Jet A-1 ($-47\text{ }^{\circ}\text{C}$). Additives are usually added to
312 biodiesel to further improve the cold flow properties. The EU and US ASTM standards require
313 the flash point for biodiesel to be higher than $120\text{ }^{\circ}\text{C}$ and $93\text{ }^{\circ}\text{C}$, respectively. When compared
314 with conventional fossil fuels, the flash point for typical biodiesel ($145\text{ }^{\circ}\text{C}$) is much higher than
315 Jet A-1 ($38\text{ }^{\circ}\text{C}$) and fossil diesel ($76\text{ }^{\circ}\text{C}$), as shown in Fig. 5. The benefit of higher flash point is
316 that storage and transportation of biodiesel becomes relatively safer.

317 Another important property is oxidative stability, which is the measure of reaction rate
318 between the fuel and oxygen. The unstable fuel reacts with oxygen to form gums, sediments
319 and other deposits which subsequently increase the viscosity of the fuel [24]. Table 3 shows
320 that only coconut, palm, rapeseed, canola and castor-based biodiesels fulfil the requirements
321 set by the EU standard (min 6 hours). Sunflower and peanut-based biodiesels are not able to
322 meet the requirement set by US ASTM standard, which is minimum 3 hours. High oxidative
323 stability indicates low degradability tendency and prolongs storage time for biodiesel. The
324 typical storage time for biodiesel is usually not more than six months [52], while diesel can be
325 stored up to 12 months at ambient temperature [53]. Biodiesel has gained much attention as
326 supplemental fuel in recent years. The US has implemented the biodiesel mixture excise tax
327 credit as part of the policy in diversifying energy portfolio [54]. The Malaysian government
328 has implemented mandatory blending of palm-based biodiesel with diesel at B7 for transport
329 and industrial sectors [55].

330

331 **2.2.2 Production of biodiesel**

332 Transesterification is the most common process used to produce biodiesel. The process
333 converts triglycerides into glycerol and biodiesel in the presence of alcohol and catalyst at

334 elevated temperature, as shown in Fig. 6. The conversion process is a stepwise and reversible
335 process where alcohol initially reacts with triacylglycerols to produce diacylglycerols and fatty
336 acid alkyl esters. Further reaction leads to the formation of monoacylglycerols and lastly
337 biodiesel and glycerol. The process is reversible, but the reversible rate is usually negligible
338 due to glycerol being not miscible with fatty acid alkyl esters [56]. The catalysts can be of acid,
339 alkaline or enzyme types, depending on the content of free fatty acid (FFA) in the feedstock
340 [57].

341 In acid catalysed transesterification, hydrochloric acid or sulfuric acid are commonly
342 used [58,59]. Acid catalysts were reported to give high yields (90%) in a relatively short period
343 of reaction time (1 to 6 hours). Meanwhile, acid catalysts can tolerate higher level of free fatty
344 acids compared to alkaline catalysts [47,60]. Apart from acid catalyst, alkaline such as alkaline
345 metal alkoxides and hydroxides, potassium carbonates and potassium hydroxide can also be
346 used as catalyst in transesterification process. Alkaline metal alkoxides was reported to produce
347 even higher yield (96%) of biodiesel in a short period of reaction time (1 to 6 hours) [57]. The
348 use of alkaline, however, is susceptible to the level of free fatty acids. The fatty acid could react
349 with alkaline catalyst to produce soap that inhibits the separation process [61]. Enzymatic
350 catalyst such as lipase was introduced to overcome the complex processing needed for the by-
351 product treatment in acid and alkali catalyst transesterification process [61]. However, low
352 yield (62% to 71%) and long reaction time (up to 8 hours) for this biodiesel production
353 technique is not favoured for mass production [62]. Another technique for biodiesel production
354 without requiring catalyst is by using methanol under supercritical condition [63]. This
355 supercritical process requires severe operating conditions such as temperature greater than
356 240 °C and pressure greater than 80 bar [64]. As catalyst is not used in this process, the by-
357 product treatment process is simpler due to the absence of contaminants. The advantage of this
358 process is short reaction time compared to catalytic-based process [63], but the disadvantages

359 are requirement of expensive equipment and high production cost [1]. Methods of producing
360 biodiesels from various types of lipids are summarised in Fig. 4.

361

362 **2.2.3 Performance of biodiesel in gas turbines**

363 Biodiesel has proven to be a viable substitute fuel or as blend with diesel in
364 compression-ignition engines due to its close resemblance to diesel in physical properties [65].
365 Further applications of biodiesel in gas turbines system for power generation and as aviation
366 fuel are envisaged. Land-based industrial gas turbine is fuel-robust in nature that allows the use
367 of biodiesel with minimal modification to the existing system but application in aviation-based
368 gas turbine requires stringent compliance to the jet fuel specification. Table 4 and 5 summarise
369 the previous combustion research related to biodiesel combustion in gas turbine type burners
370 and system. It is noted that biodiesels produced from different types of feedstock have been
371 used for testings.

372

373 ***2.2.3.1. Biodiesel spray flame characterisation using gas turbine type burner***

374 The potentials of biodiesel as gas turbine fuels have been investigated using lab scale
375 gas turbine type swirl flame burner. The advantage of using simplified burner allows
376 parametric studies, including comparison of combustion performances, flame structure,
377 emissions with baseline fuels under well-controlled environment. Chong and Hochgreb [66]
378 compared the combustion characteristics of palm [28] and rapeseed [67] biodiesels with
379 baseline diesel and Jet-A1. Biodiesel flames exhibited larger heat release area compared to that
380 of baselines [68]. Soot was not present in biodiesel flame owing to the absence of aromatic
381 rings in the fuel and the fuel-bound oxygen content that assist in the oxidation of soot during
382 combustion. The NO emissions were shown to reduce by ~25% for palm biodiesel as compared
383 to Jet A-1 and diesel at fixed power output of 6 kW [28].

384 Other researchers who have found the benefits of reduced emissions for biodiesel under
385 swirl flame conditions including Hashimoto et al. [42]. The smoke and soot emissions of
386 jatropha/diesel blends were significantly lower than that of diesel, resulting in lower flame
387 radiation intensity for the biodiesel blends flames. They demonstrated in a gas turbine burner
388 equipped with a pressure atomiser that NO_x emissions for palm biodiesel can be lowered by
389 generating finer spray droplets via increasing the atomising pressure. Finer droplets evaporated
390 at a shorter time scale, reducing localised hot regions that promotes NO_x formation due to
391 droplet burning in diffusion mode [69,70]. Erazo et al. [71] showed that the peak temperature
392 of canola biodiesel (1750 K) was lower compared to diesel (1900 K), hence lower NO_x
393 emissions were detected for the former. Li et al. [72] utilised a gas turbine type burner to
394 compare the spray and combustion properties of rapeseed biodiesel with diesel. Biodiesel spray
395 was found to exhibit longer spray penetration length and smaller spray cone angle compared
396 to diesel owing to its higher density, viscosity, surface tension and boiling point. Similar to the
397 findings shown by Chong and Hochgreb [73], rapeseed biodiesel produced lower NO_x
398 emissions by 21% compared to diesel.

399 Panchasara et al. [45] noted that inferior atomisation for biodiesel is the main factor
400 that promotes NO_x formation. Adjusting the control parameter presents an effective way to
401 improve emissions. Sequera et al. [74] atomised biodiesel using an airblast atomiser and
402 reported a reduction of CO emissions by 50% for biodiesel as compared to diesel under
403 constant fuel mass flow rates. Chong and Hochgreb [68,73] utilised a twin-fluid atomiser and
404 showed that the twin emissions reduction of NO and CO can be effectively achieved with
405 increasing ALR. Simmons and Agrawal [75] employed a flow blurring atomiser to atomise
406 biodiesel and reported a reduction of CO emissions by a factor of 2-3 when the ALR was
407 increased from 2.0 to 2.4 compared to the typical airblast atomiser. The improved emissions
408 were due to increased mixing from flow blurring. A group of researchers from Cardiff

409 investigated the spray combustion characteristics of biodiesel and biodiesel saturated with
410 pyrolysis oil. The biodiesel/pyrolysis oil blend was found to produce higher NO_x emissions
411 than kerosene, while biodiesel shows comparable NO_x with the latter [76]. Despite no
412 explanations yet can adequately elucidate the biodiesel-NO_x effect based on the previous
413 studies, some recent opinions skewed towards fuel chemistry as the fundamental cause of
414 increased biodiesel NO_x emissions [51,77,78].

415

416 ***2.2.3.2. Application of biodiesel in gas turbine system for power generation***

417 The performances of biodiesel combustion at system levels have been tested using
418 actual gas turbines, including those of micro gas turbine, industrial and aviation gas turbine
419 engines. Micro gas turbine can be used for off grid power generation for households, small
420 businesses and rural regions, thus the ability to operate on biodiesel is of interest. Bolszo and
421 McDonnell [79] operated a 30 kW MGT (Capstone C30) with soy-based biodiesel and reported
422 higher NO_x emissions than diesel fuel by approximately 13 ppm. Larger droplet size was
423 generated by biodiesel during spray atomisation, leading to higher NO_x emissions as a result
424 of longer evaporation time scale. In another separate MGT (Capstone C30) test, Krishna [80]
425 reported lower NO_x emissions by 60% and 14% for soybean biodiesel at high and low thermal
426 input, respectively, compared to fossil diesel. Both tests showed that soy-based biodiesels could
427 produce conflicting results even in the same gas turbine systems.

428 Nascimento et al. [81,82] compared the thermal performance and emissions of castor
429 biodiesel and blends with diesel in a 30 kW MGT. CO emissions were found to increase by
430 50% as compared to diesel at 14 kW engine output power. It was opined that the lower NO_x
431 emissions achieved in the MGT tests were partly contributed by the inferior atomisation of
432 biodiesel which resulted in lower combustion temperature. The size of biodiesel liquid droplets
433 and primary-zone equivalence ratio were larger for biodiesel compared to diesel. The reduction

434 of temperature in primary combustion zone (due to higher equivalence ratio) reduced the
435 emission levels of NO_x pollutants for biodiesel. For MGT that utilises air-blast atomiser, the
436 production of NO_x is affected by the variation of atomising air to liquid ratio. The increase in
437 the percentage of atomising air results in leaner combustion and lower flame temperature,
438 hence the lower NO_x emissions [68,74].

439 Habib et al. [83] utilised a 30 kW gas turbine engine to examine the performance of
440 soy, canola, recycled rapeseed biodiesel and hog-fat biofuel against Jet A. NO emissions for
441 biodiesel were consistently lower than diesel at lean-burning conditions, with a maximum
442 reduction of up to 75%, while the difference in turbine inlet and exhaust gas temperature
443 between biodiesel and diesel was less than 80 °C and 20 °C respectively. CO emissions were
444 found to be lower for biodiesels as the oxygen in the biodiesel assisted in converting CO into
445 CO₂ [83,84]. The static thrust produced by biodiesel and blends were comparable to that of jet
446 fuel. They reported that fuel efficiency was higher when operating with biodiesels, owing to
447 the oxygen in biodiesel that resulted in more complete combustion [83]. Some have reported
448 improved gas turbine performance due to the oxygen content in biodiesel [81].

449 The notion of fuel-flexible industrial gas turbine operation is attractive from the point
450 of view of lower operating cost and adaptability to local biofuel sources. Several gas turbine
451 tests have been conducted using biodiesels. Liu et al. [85] investigated the ignition, combustion
452 dynamics and emissions of biodiesel using a Siemens SGT-100 gas turbine. The NO_x emissions
453 for biodiesel were found to be lower than that of diesel for all operating conditions tested. In a
454 semi-closed cycle gas turbine field test conducted by Ellis et al. [86], soot emissions were
455 shown to reduce by 70% and 32% for palm and soy biodiesels, respectively. No significant
456 trend was observed for UHC emissions for all fuels tested despite slightly higher fuel
457 consumption rate for pure biodiesel by 4-7%. Moliere et al. [87] tested rapeseed biodiesel in a
458 GE 6531B industrial gas turbine. No visible smoke was observed during biodiesel combustion

459 and sulphur oxide emissions were less than 1 ppm. These results indicate the positive effects
460 of biodiesel towards the environment. However, there was a reported case where higher UHC
461 emissions were observed when blends of biodiesel (fish oil and canola oil based) with Jet A1
462 fuel were used in an industrial gas turbine sector rig (Allison/Rolls Royce T56-A-15
463 combustion systems), accompanied by a slight increase in engine deposits for 20% biodiesel
464 blends due to excessive gum and inferior atomisation [88]. These studies show that due to
465 complexities of gas turbine operation, extensive testings are required when using alternative
466 fuels, as the effect of fuel is not restricted to only combustion, but also downstream of
467 combustor such as the turbine blades.

468 Power generation for aviation gas turbine is another area that is extensively explored in
469 search for cleaner alternative fuels to replace fossil-based fuels. Although biodiesel is
470 oxygenated, slightly denser and contains lower heating value than conventional jet kerosene,
471 blending biodiesel with jet fuel could result in positive emission benefits without incurring
472 significant performance penalty. Timko et al. [89] achieved lower NO_x by 29% and 23% for
473 40% and 20% biodiesel blends, respectively in an aviation gas turbine engine (CFM56-7B
474 turbo-fan engine) test. In another biodiesel test in a helicopter turboshaft engine (T63-A-700),
475 Corporan et al. [90] reported that 20% soybean biodiesel/JP-8 blend produced 15% reduction
476 in particle number density at cruising and take-off conditions. Rehman et al. [84] concluded
477 that the oxygen content in a jatropha/diesel blends assisted in the combustion of a 44 kW gas
478 turbines (IS/60 Rovers). Biodiesel was shown to have better fuel efficiency than diesel despite
479 a slight reduction in brake specific fuel consumption (BSFC) by 0.5 kg/kW-hr. The blends
480 however, showed higher emissions of NO_x by 34-42% compared to diesel at the same power
481 output. It was postulated that the higher oxygen content in biodiesel led to higher flame
482 temperature and subsequently higher level of NO_x emissions. Talib et al. [91] utilised a turbojet
483 engine (Armfield CM4) to test the performance of 20% biodiesel/diesel blend compared to Jet

484 A-1 baseline. It was reported that the former fuel produced a lower thrust by 4%, as expected
485 as the energy content of biodiesel is lower than jet fuel by approximately 17% by mass [28].
486 These results showed that application of biodiesel in aviation gas turbine is feasible with the
487 benefits of lower emissions but at the expense of performance penalty.

488

489 **2.3 Hydrogenated vegetable oil (HVO)**

490 **2.3.1 Properties of HVO**

491 Hydrogenated vegetable oil (HVO) is also known as green diesel, renewable synthetic
492 diesel, hydrogenated straight vegetable oil (HSVO), hydrodiesel or hydrogenation-derived
493 renewable diesel (HDRD) [92]. Similar to SVO and biodiesel, plants such as rapeseed, palm,
494 castor, sunflower, jatropha, soybean, and animal fat have been used as feedstock to produce
495 HVO [93,94]. The advantage of HVO is its compatibility with existing diesel engine [26,95]
496 and with nearly 0% oxygen content [93,96]. The biodegradability of HVO is poorer compared
497 to SVO and biodiesel [92–94,96].

498 The calorific value for HVO is higher than that of biodiesel by 16% per mass basis and
499 is comparable with fossil diesel and Jet A-1, as shown in Fig. 5. The cetane number for HVO
500 is higher than both biodiesel and diesel, indicating reduced ignition delay time for engine. The
501 density for HVO is similar to Jet A-1, but less dense than biodiesel and diesel, which makes
502 HVO a good substitute for conventional fuels without incurring weight penalty. The low
503 freezing point of HVO (-25 °C to -40 °C) fulfils the requirement of jet fuel to avoid formation
504 of wax in the fuel supply system. Furthermore, HVO has comparable viscosity as Jet A-1 and
505 diesel. The comparable physical properties of HVO with Jet fuel has enabled the former to be
506 certified as alternative jet fuel [4].

507

508 **2.3.2 Production of HVO**

509 HVO is produced via hydrogenation of vegetable oil in the presence of catalyst and
510 hydrogen [26,95]. The process breaks the double bond (C=C) in the vegetable oil into single
511 bond (C-C). Hydrogen was inserted into the hydrocarbon chain. Apart from carbon and
512 hydrogen atoms, other elements such as sulphur, nitrogen, and oxygen are present in HVO [96].
513 The presence of these heteroatoms is highly undesirable; as oxygen tends to reduce the heating
514 value while sulphur promotes the formation of sulphur dioxide during combustion process.
515 Hydrogenation process removes these heteroatoms to improve the overall quality of the fuel
516 [26,95]. The hydrogenation process mainly consists of two steps: hydrotreatment that saturates
517 the unsaturated fat (i.e. breaking the C=C), and isomerisation process that forms the branched
518 chains [26,95].

519 The research on hydrotreatment of vegetable oils has mostly focused on the type of
520 reactors and catalysts. Two types of catalysts were reported to be effective in hydrotreatment
521 of vegetable oils process, namely metal catalysts and sulfided bimetal catalysts [94]. The
522 overall process of hydrogenation of vegetable oil is shown in Fig. 7. Feedstock is supplied to
523 the catalytic reactor to combine with hydrogen at elevated temperature and pressure. The
524 feedstock is pretreated prior sending into reactor. In the reactor, the feedstock undergoes the
525 hydrodeoxygenation, decarboxylation, and hydroisomerisation processes to convert into diesel,
526 water, and oxide of carbon [92]. The hydrotreatment process takes place in a fixed bed reactor
527 at elevated temperature of 300-400 °C and pressure of 30-130 bar in the presence of catalyst.
528 The HVO yield varies from 88% to 99%, depending on the type of feedstock [92]. The
529 produced diesel fuel contains no sulphur, oxygen, aromatic and nitrogen.

530 **2.3.3 Performance of HVO in gas turbines**

531 HVO has been identified as a promising alternative jet fuel due to the absence of oxygen
532 molecules and comparable physical properties to jet fuel [4]. A study conducted by Chan et al.
533 [97] using a turbofan engine (CF700-2D-2) fuelled with HVO has shown lower NO_x emissions

534 compared to Jet A-1. At idling conditions of 80% and 95% engine loads, the 50% HVO/Jet A-
535 1 blend produced up to 0.3 g/kg lesser NO_x than neat Jet A-1. The result concurs with Baranski
536 et al. [98] in a turbojet engine (JetCat P-200) test fuelled with HVO and JP-8, where NO_x
537 emissions for HVO were shown to be consistently lower than that of JP-8 at all operating speeds.
538 The thrust specific fuel consumption for HVO was 16% lower than that of JP-8 at engine speed
539 below 60,000 rpm.

540 Klingshirn et al. [99] reported lower CO emissions in a gas turbine (T63 A-700) test
541 fuelled with HVO compared to baseline JP-8. CO emissions were consistently lower than that
542 of JP-8 at both the idling and cruising modes with fuel/air ratios of 0.009 and 0.017,
543 respectively. The effect of altitude on the emissions of CO by hydrogenated fuel was
544 investigated by Chishty et al. [100]. The gas turbine performance test was conducted at the
545 altitudes of 1525 m and 6095 m with Jet A-1 and blend of 50% JP-8/hydrogenated renewable
546 jet fuel. Jet A-1 showed higher CO emissions as compared to the blend. The exhaust CO was
547 around 175 g/kg fuel at 6095 m, which is significantly higher than at 1525 m which was about
548 125 g/kg fuel. Jet A-1 showed slightly higher NO_x emissions than JP-8/hydrogenated fuel blend
549 by a slight difference of 0.3 g/kg fuel.

550 The improved emission performance of HVO was also reported by Purcher et al.
551 [88,101] in a gas turbine (Allison/Rolls Royce T56-A-15) test operated with HVO. The
552 particulate matter and unburned hydrocarbon emissions were reduced by 96% and 27.7%
553 respectively as compared to baseline Jet A-1. HVO has shown overall positive emissions as
554 opposed to that of fossil jet fuel. Soot concentration and mass deposition were found to reduce
555 significantly for HVO. On top of that, the ignition delay time is also shorter and resistance to
556 extinction is stronger compared to Jet A [102]. Buffi et al. [103] investigated the heat release
557 and emissions profiles of Jet A-1, HRJ (Hydrotreated Renewable Jet Fuel) and their blends
558 using an optical swirl burner. It was reported that HRJ exhibited a more homogenous heat

559 release zone that led to reduced emissions. Meanwhile, the effect of backpressure was also
560 examined, whereas the reduced bulk flow was due to the increase of backpressure that formed
561 a more compact flame brush.

562

563 **2.4 Bioethanol**

564 **2.4.1 Properties of bioethanol**

565 Bioethanol is a colourless, biodegradable, low toxicity, and highly flammable liquid.
566 Bioethanol has relatively low viscosity (1.5 mm²/s) and pour point (-78 °C) which are
567 comparable to jet fuel, as shown in Fig. 5. However, the downside of bioethanol is its low
568 calorific value (only around 63% of fossil diesel) and low flash point (14 °C). In addition, the
569 low flash point characteristic makes bioethanol an explosive hazard [104].

570

571 **2.4.2 Production of bioethanol**

572 Bioethanol is produced by fermentation of sugar units derived from the sugar-
573 (sugarcane, sugar beet), starch- (corn, wheat, barley) or cellulosic- (rice straw, wheat straw,
574 wood) based biomass [105]. The pure sugar biomass feedstock (sugarcane and sugar beet) is
575 relatively straightforward to be converted into bioethanol, due to fermentable sugar units that
576 can be obtained relatively easy during extraction process of raw material. Starch-based
577 feedstock such as corn and wheat are more complicated due to the long chain polymers of
578 glucose that cannot be directly fermented. The polymers have to be broken down into
579 monomers before fermentation process [106–108]. Cellulosic feedstock such as wood, straw
580 and bagasse are the most difficult feedstock to breakdown as compared to sugar and starchy
581 biomass due to their constituent parts [106–108].

582 The production process of bioethanol consists of (i) pre-treatment, (ii) hydrolysis, (iii)
583 fermentation and (iv) purification processes [106–110], as shown in Fig. 4. The purpose of pre-

584 treatment is to break the lignin and cellulose structure of the feedstock to make the feedstock
585 more susceptible to enzymatic attack in hydrolysis process. Sugar biomasses such as sugarcane
586 and sugar sorghum are usually mechanically crushed to extract the sugary juice from their
587 stalks. For starchy-based feedstock, the dry or wet milling processes are commonly used [106–
588 109]. Lignin provides the rigid structure for cellulosic feedstock. Thus, the conversion of
589 lignocellulosic feedstock into ethanol is more difficult compared to sugar and starch based
590 feedstock [106–108]. Steam explosion is one of the pre-treatment methods for cellulosic
591 feedstock, whereas the feedstock is exposed to high pressure saturated steam to break the lignin
592 structure so that the feedstock is more susceptible to hydrolysis [106,110].

593 Following the pre-treatment is the hydrolysis process which degrades the cellulose and
594 hemicellulose from the raw material into simple sugar units for the fermentation process.
595 Enzymatic hydrolysis has the advantage over the chemical hydrolysis for its lower cost [105].
596 Cellulase enzymes are typically used to convert the complex cellulose and hemicellulose into
597 simple monomers [111–113]. Fermentation is the process in which sugar units are converted
598 into bioethanol due to the enzymes secreted by microorganisms. Baker’s yeast (*Saccharomyces*)
599 is usually used to convert the glucose into ethanol [105]. Factors that affect the efficiency of
600 fermentation are pH range, genetic stability, temperature range, inhibitor tolerance, and alcohol
601 tolerance [105]. More complex sugar unit such as pentose and hexoses are usually more
602 difficult to be fermented compared to glucose. Nonetheless, several methods have been
603 introduced for pentose and hexoses fermentation, these include using genetically modified
604 microbes [108,114], combination of both fermentation and enzyme hydrolysis [115], mixed
605 cultures of yeasts [116] and fermentation of the pentose and hexose sugars simultaneously in a
606 single reactor by a single microorganism’s community [108,109,117].

607

608 **2.4.3 Performance of bioethanol in gas turbines**

609 Bioethanol is commonly utilised as replacement for gasoline to power the internal
610 combustion engine. One of the commonly used bioethanol blends is E85, which contains 85%
611 bioethanol/ethanol and 15% gasoline. Ethanol-gasoline blends with minimum 10% ethanol
612 proportion are known as gasohol. Gasohol is common in countries such as Brazil, Denmark
613 and the US [118]. Sallevelt et al. [119] examined the emissions of bioethanol combustion in a
614 gas turbine engine (OPRA 2MWe OP16). NO_x emissions for bioethanol were 50% lower than
615 that of diesel for equivalence ratios between 0.15 - 0.35 due to lower thermal NO_x. Moliere et
616 al. [120] reported that neat bioethanol emits 50% NO_x lower as compared to neat naphtha in
617 an industrial gas turbine (GE Frame 6B). Despite lower emissions of NO_x for bioethanol, CO
618 emissions were rather inconsistent [119–121]. Santos and Nascimento [122] fuelled a 30 kW
619 gas turbine with bioethanol at different loadings. A slight increase in CO was observed.
620 Meanwhile, Khalil and Gupta [121] examined the combustion and emissions performance of
621 bioethanol using a swirl burner. Fuel and preheated air were premixed upstream of the
622 combustor prior to injection into the combustion chamber at high velocity (96 m/s) tangentially
623 and in swirling mode. Bioethanol was shown to produce lower CO emissions as compared to
624 kerosene under lean burning mode. Maximum reduction of was up to around 40 ppm at
625 equivalence ratio of 0.8. The decrease in CO emissions was attributed to the excess oxygen
626 that converts CO to CO₂.

627 Breaux and Acharya [123] studied the effect of water content in ethanol combustion
628 using a swirl burner. It was found the water content reduced the flame temperature. When water
629 content is below 20%, the effect of water on combustion performance was only minor and
630 regarded as insignificant. However, as the water content increased beyond 20%, it impaired the
631 continuous combustion process. Due to reduced flame temperature, NO_x emissions were found
632 decreased from 13 ppm to 3 ppm for 0% and 30% of water content, respectively. Kun-Balog
633 et al. [124] experimentally investigated the emission characteristics of bioethanol in both liquid

634 and aqueous form against diesel and natural gas (NG). The experiment was conducted using a
635 lab-scale swirl burner. The use of bioethanol resulted in 44% lower NO_x than diesel under the
636 same thermal power output, which was attributable to the lower adiabatic flame temperature.
637 The CO and UHC emissions were relatively low for bioethanol. However, aqueous bioethanol
638 resulted in higher NO_x than its liquid counterpart.

639

640 **2.5 Bio-oil**

641 **2.5.1 Properties of bio-oil**

642 Bio-oil is liquid fuel obtained from the biomass pyrolysis. Bio-oil is also known as
643 pyrolysis oil or bio-crude [125]. It is usually dark brown in colour and consists of organic
644 compounds mixture. The pyrolysis process for the production of bio-oil involves heating of
645 organic compound such as cellulose, hemicellulose and lignin in the absence of oxygen [125].
646 The process produces a range of products including char, bio-oil, and gaseous products. The
647 composition of bio-oil depends on the temperature of the pyrolysis process [105]. At pyrolysis
648 temperature below 600 K, formation of char is dominant. At temperature beyond 800 K,
649 gaseous formation is dominant due to increased reaction rates that break the bond between
650 carbons. For temperature in between 600 K and 800 K, bio-oil formation is dominant [105].
651 Table 6 shows the composition of bio-oil derived from several feedstocks [126]. Feedstock
652 with high water content such as barley straw produces bio-oil with lower calorific value.
653 Typical pyrolysis oil produced from feedstock with moderate water content (20-27% wt)
654 contains approximately 15-16 MJ/kg of calorific value. While it was demonstrated that palm
655 oil sludge is a promising feedstock, bio-oil produced from palm oil sludge resulted in notably
656 higher calorific value (22.2 MJ/kg) and lower ash contents (0.23 wt%) [127].

657 Bio-oil is corrosive as it contains substantial amount of formic and acetic acids. Other
658 trace elements such as sodium, calcium, potassium, and vanadium in pyrolysis oil are

659 undesirable as they lead to formation of solid deposition [125,128]. The viscosity of bio-oil is
660 relatively high (15.5 mm²/s). These undesirable properties of bio-oil have restricted the usage
661 in practical combustion system [129] despite having the advantages of being renewable,
662 sustainable and potentially CO₂ neutral. Post-production methods have been introduced to
663 improve the properties of bio-oil such as (i) hydrodeoxygenation, (ii) hydro-cracking, (iii)
664 emulsification, (iv) steam reforming and (iv) esterification to enable applications in combustion
665 systems [130].

666

667 **2.5.2 Production of bio-oil**

668 Bio-oil can be produced by 3 different processes, i.e. (a) conventional pyrolysis; (b)
669 fast and flash pyrolysis and (c) hydrothermal liquefaction (HTL) [105,130], as shown in Fig.
670 4. Conventional pyrolysis operates in the temperature range of 300-650 °C. The residence time
671 is relatively long, typically exceeding half an hour for each batch. Recent studies showed that
672 the yield of bio-oil can be increased with elevated temperature and residence time [131]. The
673 process breaks up the chemical bonds in the feedback, leading to the formation of pyrolysis
674 products [105,130,132]. Fast pyrolysis requires higher operating temperature (650-1000 °C) to
675 decompose the feedstock. The feedstock for pyrolysis can be of any organic biomass. Wood,
676 agricultural wastes, crops, and sewage sludge have been utilised as feedstock for this process
677 [130]. Due to high operating temperature, short residence time of less than 0.2 hour is required.
678 The rapid heating of biomass leads to the formation of volatile vapours, aerosols and char.
679 After rapid cooling, the volatile vapours and aerosol condense into bio-oil [128,133,134].

680 Flash pyrolysis operates at the temperature as high as 1200 °C. This process requires
681 the shortest residence time (< 0.1 hour) as compared to other forms of pyrolysis. A major
682 advantage of flash pyrolysis is the improved overall energy efficiency of the process

683 [105,130,132]. The reactor used for fast and flash pyrolysis has to be able to achieve high
684 heating and heat transfer rate to minimise the formation of char.

685 Hydrothermal liquefaction (HTL) produces bio-oil in an aqueous medium that
686 involves a series of complex processes such as solvolysis, dehydration, decarboxylation, and
687 hydrogenation. The typical operating conditions are temperature ranging 300-400 °C, pressure
688 up to 20 bar, and residence time of 0.2-1 hour. The primary product derived from this process
689 is bio-oil. Contrary to fast and flash pyrolysis, feedstock drying is not necessary, making it
690 suitable for wet biomass [130].

691

692 **2.5.3 Performance of bio-oil in gas turbines**

693 Gas turbine fuelled with bio-oil generally emits lower NO_x emissions as compared to
694 baseline fuels [135,136]. Beran and Axelsson [136] studied the combustion properties of bio-
695 oil using a micro gas turbine (OPRA OP-16). Emission results showed that NO_x emissions of
696 bio-oil was 25% of that emitted by diesel at full engine loading, which is expected considering
697 the lower calorific of bio-oil (37.6%) compared to the latter. Zheng and Kong [137] studied the
698 emissions of rice husk bio-oil using a combustor fitted with an internal-mixed atomiser. Results
699 showed that NO_x concentration increased from 211 to 370 ppm while SO_x concentration
700 increased from 11.6 to 25.9 ppm as equivalence ratio increased from 1.2 to 2.0. The increase
701 of NO_x emissions was due to oxidation of nitrogen in post-flame region and oxidation of
702 nitrogen compounds in the fuels.

703 Lopez Juste and Salva Monfort [138] compared the combustion performance of JP-4
704 and 80% bio-oil/ethanol blends by using a gas turbine burner equipped with pressure swirl
705 atomiser. The emissions of NO_x for bio-oil/ethanol blend were found to be similar to JP-4 at 1
706 MJ/kg energy input. At a higher energy input of 1.36 MJ/kg, NO_x emissions for JP-4 were 4
707 times higher than bio-oil, possibly due to higher flame temperature exhibited by JP-4. Lupadin

708 et al. [135] compared several types of alternative fuels against diesel by using a 2.5 MW gas
709 turbine (GT2500) as shown in Table 7. For bio-oil, higher fuel flow rate was needed to achieve
710 comparable output power and exhaust gas temperature as baseline diesel. The fuel flow rate
711 required by diesel to generate 2510 kW of output power was 1071 l/hr while bio-oil required
712 1800 l/hr of fuel supply to generate 2650 kW of output power. The exhaust gas temperature for
713 both fuels was only differ by 17 °C. Bio-oil emitted higher CO and lower sulphur oxide
714 emissions compared to baseline fuels.

715 Zadmajid et al. [139] reported that bio-oil and 80/20 bio-oil/ethanol blend showed high
716 emissions of CO at 2284 and 650 ppm, respectively, under swirl burning condition. By using
717 a modified burner with increased swirl and main air supply, the CO and UHC emissions
718 showed significant reduction to below 10 ppm. Apart from burner geometry, the choice of
719 feedstock and quality of bio-oil are important factors that determine the level of emissions.
720 Table 6 shows that bio-oil produced from wood contains higher calorific value and lower
721 viscosity than the other feedstock. Although combustion of bio-oil has shown lower sulphur
722 and nitrogen oxide emissions, direct usage of bio-oil in gas turbine are limited due to inherent
723 inferior properties such as high viscosity and acidity level. Direct bio-oil usage caused high
724 level of particulate matter emissions, while other issues related to bio-oil are solid deposition
725 on turbine due to the presence of trace elements and fuel nozzle blockage during operation
726 [140]. The high viscosity of bio-oil affects fuel atomisation which subsequently leads to
727 reduced combustion efficiency. Preheating of fuel and improvement in atomisation technique
728 can be applied to reduce fuel viscosity. Crayford et al. [141] reported that bio-oil exhibited
729 spray characteristics similar with diesel when preheated the fuel to 80 °C.

730 **2.6 Fischer-Tropsch (FT) fuel**

731 **2.6.1 Properties of FT fuel**

732 Fischer-Tropsch (FT) synthesis refers to the process of converting syngas into liquid
733 fuels at high temperature conditions in the presence of catalyst [105,132], as shown in Fig. 4.
734 FT fuels are clean compared to fossil fuels due to the absence of nitrogen, sulphur, and
735 aromatics. Hydrocarbon fuels of different chain length can be produced from FT synthesis via
736 any feedstock that contains carbon, e.g. coal, biomass and natural gas. It has been reported that
737 FT fuel is compatible with existing jet engine systems [105] with calorific value of 43 MJ/kg,
738 viscosity of 1.3 mm²/s at 40 °C and density of 810 kg/m³ at 15 °C (Fig. 5). These properties
739 are comparable with Jet A-1, making it a potential alternative jet fuels besides HVO [26,142].

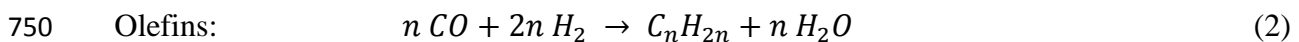
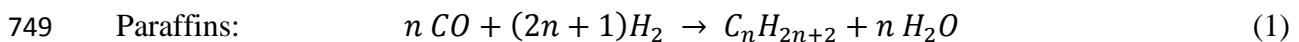
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741 **2.6.2 Production of FT Fuel**

742 The process of producing FT fuel consists of three main stages as shown in Fig. 8: (i)
743 gasification of biomass into syngas; (ii) gas cleaning and conditioning, and (iii) FT synthesis
744 to produce liquid fuel [105].

745 The FT process is essentially a stepwise hydrocarbon chain growth process that
746 disintegrates the carbon monoxide and hydrogen in the syngas to form mainly paraffins and
747 olefins as shown in reactions 1 and 2 [143]:

748



751

752 Both reactors and catalyst are the governing factors that control the products of FT
753 synthesis. Three reactors have been designed and widely used for FT fuel synthesis, namely
754 fixed bed, fluidised bed and slurry reactors [105], as shown in Fig. 9. Fixed bed reactors consist
755 of catalyst tube bundles immersed in steam, whereby the heat from the surrounding steam is
756 absorbed to achieve the FT synthesis process as syngas flows through catalyst tube bundles.

757 Despite easier to operate, the major drawback is its high capital cost and maintenance work
758 that involves high cost and long down time, which impairs the overall efficiency of the plant
759 [144].

760 In a fluidised bed reactor, the syngas is heated up before it is exposed to the catalyst.
761 Fluidised bed reactors possess higher heat exchange efficiency compared to fixed bed reactor
762 due to the circulating flow design. The construction of the reactor is also simpler which greatly
763 reduced the overall production cost. On the other hand, catalyst removal from the reactor is
764 also simpler which reduces maintenance time. However, expensive scrubbing system is needed
765 to separate the small catalyst particles from the outlet gas [105,144].

766 In slurry reactors, the catalyst is suspended in the liquid where the syngas is bubbled.
767 Heat is supplied by the steam flow. Slurry reactors possess excellent heat transfer, thus
768 increases the overall process efficiency. In addition, the ease of catalyst replacement also
769 reduces production cost. The down side of it is the difficulty in separating the catalyst and wax
770 [144,145]. Different types of reactors have their own advantages and disadvantages, the
771 optimum choice depends on the final target products and operating conditions [105].

772

773 **2.6.3 Performance of FT fuel in gas turbines**

774 The use of FT fuel in gas turbines has been widely researched. Hermann et al. [146,147]
775 examined the performance of FT fuel using a Volvo Aero gas turbine (VT40). FT fuel achieved
776 higher combustion efficiency compared to Jet A-1 for equivalence ratio of 0.1 to 0.2, with a
777 maximum improvement around 2%. Meanwhile, higher NO_x (>3 g/kg) was emitted by FT fuel
778 due to higher flame temperature compared to Jet A-1 (<3 g/kg). However, NO_x emissions
779 against Jet A-1 were also found to be reduced [97,148]. Chan et al. [97] compared the
780 performance of synthetic kerosene with aromatics (SKA), FT synthetic paraffinic kerosene
781 (SPK), and 50-50 blend of Jet A-1 and hydroprocessed SPK using a turbofan engine (CF700-

782 2D-2). It was reported that FT fuel led to a reduction in NO_x emissions. At 80% engine loading,
783 neat FT fuel achieved a reduction of 32% in NO_x compared to Jet A-1 due to lower primary
784 zone temperature. The CO emissions tend to show a reduction trend when compared with
785 conventional jet fuels [149–151]. Lobo et al. [149,150] compared the emissions of FT fuel
786 against Jet A-1 using a CFM56-7B gas turbine engine. A reduction of 5–10% in carbon
787 monoxide was achieved by FT fuel due to lower fuel viscosity.

788 Bulzan et al. [152] operated a CFM56-2C1 gas turbine engine fuelled with FT fuel and
789 JP-8. The emission data showed that sulphur dioxide emissions for JP-8 was higher than that
790 of FT fuel by a factor of 2. The low SO_x emissions was due to the absence of sulphur in the FT
791 fuel. Furthermore, soot emissions have been consistently lower for FT fuels compared to
792 baseline fossil fuels [97,100,149–155]. The reduction in soot is largely attributed to the absence
793 of aromatic rings in the fuel [156,157].

794 Corporan et al. [158] studied the particulate matter emissions of FT fuel using a T63
795 turboshaft engine and a swirl stabilised combustor. Particulate matter (PM) emissions for neat
796 FT fuel, blend of FT fuel/JP-8 (75/25, 50/50 and 75/25) and neat JP-8 were compared. They
797 found that FT fuel produced the finest particle size compared to blended fuel and neat JP-8.
798 During cruising conditions, particle mass for FT fuel was 95% smaller compared to JP-8, which
799 was attributable to the reduction in soot nuclei. Sulphur oxide emissions for FT fuel were also
800 lower as compared to neat JP-8. Bester and Yates [153] also reported significant reduction in
801 soot for FT fuel by 86.8% compared to baseline fuel. The improved soot oxidation by FT fuel
802 combustion led to reduced fluid flow frictional losses in combustor, thus contributing to an
803 improved thermal efficiency. Thermal efficiency for FT fuel engine was increased by an
804 average of 1.17% at cruising condition. The improvement was attributed to the higher H/C ratio
805 of FT fuel compared to Jet A-1. Table 8 summarises the combustion tests of FT fuel conducted
806 in gas turbine engines.

807 Transient, ignition and extinction performance of gas turbine engine powered by FT
808 fuel have been widely researched. Vukadinovic et al. [159] investigated the combustion
809 characteristic of FT fuel, Jet A-1 and aromatics-enriched FT fuel using a combustion vessel.
810 Although all of the tested fuels exhibited similar laminar flame velocity for equivalence ratios
811 0.6 - 1.5, the extinction resistance characteristic for FT fuel was observed to be stronger than
812 that of Jet A. Conversely, Moses et al. [154,155] found no distinct difference in the ignition
813 and extinction performance for synthetic jet fuel and Jet A-1. The study was conducted using
814 a Pratt & Whitney JT-9D engine with a series of take-off cycles was imposed on the engine.
815 There was no significant degradation on engine performance when using synthetic jet fuel. In
816 addition, synthetic jet fuel showed nearly 22% droplet size reduction against Jet A-1 at -40 °C.
817 Davidson et al. [160] showed that neat FT fuel was more fuel efficient than Jet A-1 in
818 a test using a General Electric CF-700-2D-2 engine. At 80% engine loading, the neat FT fuel
819 achieved 113.5 kg/kN-hour specific fuel consumption, while Jet A-1 achieved 114.5 kg/kN-
820 hour. For transient testing, FT fuel showed slightly slower shaft speed acceleration as compared
821 to Jet A-1. In another testing using TRS-18 gas turbine engine, Davidson et al. [161] reported
822 that there was no significant difference in transient shaft acceleration between FT fuel and Jet
823 A-1. Meanwhile, all fuels tested showed comparable specific fuel consumption at steady state
824 conditions. In real flight tests, synthetic jet fuels showed no obvious sign of engine performance
825 deterioration. Transient engine speed acceleration was comparable to baseline fossil jet fuels
826 [162,163]. The findings were consistent with laboratory testing, implying that FT fuel is a
827 viable alternative jet fuel.

828

829

830 **3.0 Considerations of alternative fuels as gas turbine fuels**

831 The inferior viscosity of SVO restricts its usage in existing gas turbine system. Fuel
832 preheating is an effective method to reduce the fuel viscosity. The use of twin-fluid atomiser
833 and elevating the ALR can be deployed to atomise the viscous SVO [14,43,44]. Other
834 atomisation techniques such as flow-blurring atomisation [39] and superheated steam
835 atomisation [40] may be incorporated into fuel preheating system to improve atomisation
836 quality. Nonetheless, comprehensive studies are needed as these techniques are still widely
837 under-researched, leading to a lack of thorough understanding on the overall effect on gas
838 turbine operation.

839 Although combustion performance of SVO can be potentially improved via
840 advancement in fuel delivery and atomisation technologies, extensive use of SVO may lead to
841 adverse environmental and socioeconomic effects. Ji and Long [164] concluded from their
842 study that overwhelming land occupation for feedstock plantation of first generation SVO
843 causes habitat fragmentation and bio-invasion. Furthermore, Koizumi [165] reported a direct
844 competition between agricultural based biofuel feedstock and food production. Elevating the
845 production of agricultural based biofuel feedstock also gives rise to the cost of agricultural
846 commodity [165]. The advantages of SVO include the simple production process, storage ease
847 and near zero toxicity. However, the use of SVO should not be prioritised for large-scale power
848 generation as the fuel used will divert food away from the market and incurs adverse ecological
849 dilemma.

850 Direct usage of bio-oil in gas turbine is also limited by its high viscosity. Moreover, the
851 high bio-oil acidity level, high particulate matter (PM) emissions, solid deposition on turbine
852 due to the presence of trace elements and fuel nozzle blockage during operation are additional
853 drawbacks that inhibit direct bio-oil usage in gas turbine [140]. Thus, upgrading the physical
854 properties of bio-oil is a more promising approach to expedite its mainstream application in
855 gas turbine. Among many types of upgrading methods, esterification/solvent addition is

856 undoubtedly the most practical way of enhancing the physical properties of bio-oil owing to its
857 simplicity and involves substantially lower cost [128]. Alcoholic fuels, diesel and biodiesel are
858 possible solvents that have been proposed [166,167]. Nonetheless, endeavour studies are
859 required to acquire overall understanding on the effect of blending ratio on gas turbine
860 performance, long term operation and material compatibility.

861 Bio-oil can be produced from a variety of organic feedstock such as lignocellulosic,
862 plant and agricultural waste. Diversified bio-oil feedstock minimises its negative
863 socioeconomic and ecological impacts. Nonetheless, physical properties of bio-oil produced
864 from different feedstock are varied. Spray combustion characteristics and emission
865 performance of bio-oil are greatly affected by its compositions such as ash, tar, char, water and
866 nitrogen contents. Comprehensive studies are needed to characterise their individual influence
867 on gas turbine performance. Bio-oil specifications for various gas turbine applications can be
868 subsequently formed based on parametric studies.

869 For bioethanol, current findings show that is cleaner than fossil-based fuels with
870 considerable lower emissions of NO, CO and UHC at identical thermal output power [124].
871 The calorific value of bioethanol is inherently lower than diesel and natural gas, thus increasing
872 fuel supply to achieve the identical thermal output power with fossil fuels could undesirably
873 elevate the overall operating cost. Instead of totally replacing fossil fuel, bioethanol can be used
874 as supplementary fuel to be blended with conventional or more viscous fuels. Choi et al. [168]
875 blended ethanol with biocrude-oil and showed a reduction in CO emissions against neat ethanol
876 and biocrude-oil. Martin and Boateng [169] reported that blending switchgrass pyrolysis oil
877 with ethanol in 20/80 ratio by weight achieved comparable CO emissions with neat ethanol but
878 the NO emissions increased considerably. Table 9 compares the feasibility and considerations
879 of different alternative fuels as gas turbine fuels.

880 Biodiesel has shown to be a viable biofuel in industrial gas turbine in view of its
881 comparable properties with conventional fuels. The stringent requirement of jet fuel
882 compliance limits the application of biodiesel in aviation-based gas turbine, as shown in Table
883 10. Land-based industrial gas turbine is fuel-robust by design, allowing the use of biodiesel.
884 The similarity in physical properties between biodiesel and diesel enables the application of
885 the former in gas turbine with minimal modification to the existing system. Gas turbine
886 manufacturers have introduced fuel-flexible gas turbine that allows the usage of biodiesel
887 [12,13]. Present studies focus heavily on first and second-generation biodiesels. The shifting
888 trend into third generation biofuel uptake prompts future research to investigate the combustion
889 characteristics of biodiesel made from third generation feedstock such as algae.

890 Despite the successful test flights with HVO/jet-fuels blends ascertaining its capability
891 for future aviation and power generation industries [171], current studies provide only limited
892 understanding on HVO combustion characteristics in gas turbine. Owing to the difference in
893 chemical composition against conventional jet fuels, thorough understandings on fundamentals
894 HVO combustion characteristics is essential, which include properties such as flame speed,
895 extinction, reactive species quantification effects on combustion performance [172].
896 Furthermore, assessment of HVO life cycle analysis is also important. Depending on the
897 feedstock types, CO₂ life-cycle for HVO can vary significantly [171]. This is primarily due to
898 HVO being produced from SVO at present stage [94]. Apart from SVO, it was also reported
899 that bio-oil can be converted into HVO via hydrodeoxygenation process [93,94]. This
900 inherently minimises its negative socioeconomic and ecological impacts since wide variety of
901 organic matters can be used as feedstock for producing bio-oil [94,132]. Nonetheless, technical
902 difficulties currently faced by hydrodeoxygenation process include optimum catalyst selection
903 for bio-oil from different feedstock [94]. The optimum temperature selection is another key
904 element in hydrodeoxygenation process to eliminate oxygen contents and elevating the

905 calorific value of HVO produced [94]. In essence, HVO shows comparable physical properties
906 and combustion performance to conventional jet fuels, but sustainable feedstocks such as bio-
907 oil, second and third generation feedstock should be prioritised for future HVO production.

908 FT fuel has demonstrated superior emissions, transient, ignition and extinction
909 performances against fossil-based jet fuels. Despite the proven feasibility of FT fuel as
910 alternative jet fuel [173], the high production cost prohibits its wide usage. Biomass is regarded
911 as cleaner feedstock option as compared to coal. It is projected by the International Air
912 Transport Association (IATA) [173] that the cost of synthetic jet fuels will approach those of
913 conventional jet fuels by year 2030 due to the climate change policies that favours
914 diversification of energy sources and lower production cost.

915

916 **4.0 Conclusions**

917 The production methods and properties of six potential alternative liquid biofuels for
918 gas turbine and their combustion performances have been reviewed. HVO and FT have
919 physical properties that resemble jet fuels. The long-chain hydrocarbon of FT fuel and HVO
920 has no oxygen molecule and contains energy density similar to that of jet fuel. The main
921 advantage of these fuels is low pour point that enables application in aviation gas turbine
922 especially at high altitude. Aviation gas turbine tests have shown comparable performance as
923 jet fuel with improved particulate matter emissions. Extensive use of FT fuel and HVO at
924 present stage is mainly inhibited by the high production cost. Biodiesel has slightly poorer
925 physical properties as compared to conventional fossil fuel, notably lower energy content,
926 slightly higher viscosity and density and high pour point. However, biodiesel tend to exhibit
927 cleaner combustion characteristics, as shown by the lower NO_x, CO and soot emissions. The
928 fuel-bound oxygen content can assist local combustion and prohibits the formation of soot.

929 Biodiesel is a good fuel candidate for stationery gas where the requirement is less stringent as
930 compared to jet fuels.

931 SVO and bio-oil are potential fuels for micro gas turbines, but the inherent nature of
932 high viscosity and density may result in fuel flow delivery and clogging of atomizer orifice.
933 Modified fuel delivery system with heating capability and improved atomisation technique can
934 be applied to overcome the limitations of the fuels. Bioethanol is another possible choice of
935 biofuels for gas turbine. The properties of bioethanol differ significantly from diesel as the
936 former has low flash point, low viscosity and high vapour pressure. Application of this fuel in
937 gas turbine requires modification in the fuel delivery and fuel storage systems. Studies of
938 bioethanol in gas turbine are relatively scarce although the fuel is widely applied in
939 reciprocating gasoline engine. This review shows that the robust nature of gas turbine and the
940 development of multi-fuel capable gas turbine enable operation with biofuels. This approach
941 is beneficial to the operators from the standpoint of meeting emission targets and reducing
942 operating costs.

943

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948

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