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# Utilization of biomass-derived pyro-oils in compression ignition (CI) engines – Recent developments

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**ABSTRACT**

Recent developments in different aspects of pyrolysis technology such as input energy and waste feedstocks were discussed in the study. Insights into the utilization of pyro-oils in compression ignition (CI) engines were highlighted along with the engine behavior assessment. Performance (thermal efficiency), combustion (in-cylinder pressure rise and heat release rate), and emission (hydrocarbons (HC), carbon monoxide (CO), smoke, and oxides of nitrogen) behaviors of CI engines, fueled with pyro-oils, were compared with conventional base diesel operation. Most of the literature supported a slight reduction in the thermal efficiency of the engine with the employment of pyro-oils due to lower calorific value. Combustion behavior of pyro-oil-fueled engines is almost comparable with conventional diesel operation. All carbon-derived emissions such as HC, CO, and smoke decreased with the use of pyro-oils in engines. However, some investigations reported fluctuating trends for the emissions. Overall, it may be concluded based on the comparative analysis of engine behavior that pyro-oils derived from different biomass feedstocks could be used for engine application with comparable performance and emission behaviors. However, the significant challenges related to char removal from biomass-derived pyro-oils and engine's fuel line system need to be resolved for effective employment of pyro-oils in engine applications.

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## Introduction

International Energy Agency's latest market forecast revealed that modern bioenergy will have the predominant growth in renewable resources between 2018 and 2023, employing its critical role in building a robust renewable portfolio and ensuring sustainable energy system (Dudley 2017; World Eenergy Outlook 2016). Global investments in the energy sector in terms of biomass and biofuels are encapsulated in Table 1, which demonstrates a tremendous growth in the bio-energy field (REN21 2016). In this direction of progress, G7 and G20 governments made high-profile agreements to promote renewable energy systems and applications across the world (REN21 2016). The United Nations General Assembly adopted a dedicated Sustainable Development Goals on Sustainable Energy for All (REN21 2016). Similarly, the Ministry of New and Renewable Energy, Government of India, has initiated a number of outcome-based programs for bioenergy-based technology penetration into the market in various sectors including power generation and transport sector in India. For example, Biomass Power and Cogeneration Programme was implemented in the year 2015 for grid power generation in India (Biomass Power and Cogeneration Programme, 2010). Statewide-commissioned biomass-based power

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Table 1. Global investment (billion USD) in biomass and biofuel sectors, 2005–2015 (REN21 2016).

| Year | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biomass and waste to energy | 9.7 | 11.9 | 16.2 | 17.1 | 14.7 | 15.7 | 18.0 | 13.5 | 10.5 | 10.4 | 6.0 | 14.8 |
| Biofuels | 7.3 | 7.6 | 6.7 | 7.6 | 6.2 | 7.9 | 7.2 | 6.4 | 5.5 | 5.5 | 3.9 | 6.4 |

generation projects in the country are summarized in Table 2. It is observed from the table that the total power generation capacity of 4831 MW was installed by 2016. Maharashtra, Karnataka, and Uttar Pradesh states are the leading states with high power-generation capacities (1220, 872, and 842 MW) in the country. A wide variety of biomass feedstocks were used to produce liquid fuels including biodiesel by many researchers (Ong et al. 2019; Silitonga et al. 2019, 2020).

Biomass is utilized to generate power by using different thermochemical technologies such as direct combustion, gasification, and pyrolysis (Shafie et al. 2012). Out of these technologies, biomass pyrolysis is a sustainable technology when it is integrated with solar renewable energy (Meier and Steinfeld 2010; Weimer 2012). Pyrolysis is the conversion process of biomass to liquid (pyro-oil), gas (pyro-gas), and solid (biochar) products at the temperature range of 250–800°C in the absence of oxygen (Hassan, Lim, and Hameed 2016; Islam et al. 2010; Peters, Iribarren, and Dufour 2015; Roy and Dias 2017). Various kinds of feedstock such as waste plastics (Zhao et al. 2018), electronics waste/computer waste (Suresh et al. 2018), municipal solid waste (Part et al. 2018), grassy biomass (Ansari and Gaikar 2019), Napier grass (Suntivarakorn et al. 2018), microalgae (Andrade, Barrozo, and Vieira 2018), chicken litter waste (Weldekidan et al. 2019), and tire waste (Miandad et al. 2018) could be converted into valuable liquid fuels by pyrolysis technology. As physiochemical properties of these liquid fuels (pyro-oils) are favorable for efficient combustion, they may be used for internal combustion engine applications (Damodharan et al. 2018; Mangesh et al. 2017), industrial heating applications, and small-scale power generation (Chintala 2018). As internal combustion engines cater to the huge need for transportation and power generation, the current study is focused on addressing the utilization aspects of pyrolyzed bio-oil in compression ignition (CI) engines. Deeper insights into the influence of pyrolyzed oil utilization on engine behavior are presented in the study.

## Recent developments in biomass pyrolysis technology

About 100 million EUR is to be invested for bio-oil production by pyrolysis technology in the Netherlands (Finland first for Dutch pyrolysis technology developers -Bioenergy International 0000). The current state of the art in pyrolysis technology is the integration of solar renewable energy for

Table 2. Statewide-commissioned biomass power-generation (MW) projects in India (Biomass Power and Cogeneration Programme, 2010).

| State | Up to March 31, 2012 | 2012–2013 | 2013–2014 | 2014–2015 | 2015–2016 | Total, MW |
|---|---|---|---|---|---|---|
| Andhra Pradesh | 363.25 | 17.5 | – | – | – | 380.75 |
| Bihar | 15.5 | 27.92 | – | – | – | 43.42 |
| Chattisgarh | 249.9 | – | 15 | 15 | – | 279.9 |
| Gujarat | 20.5 | 10 | 13.4 | 12.4 | – | 56.3 |
| Haryana | 35.8 | 9.5 | – | – | – | 45.3 |
| Karnataka | 441.18 | 50 | 112 | 111 | 158 | 872.18 |
| Madhya Pradesh | 8.5 | 7.5 | 10 | 9 | – | 35 |
| Maharashtra | 603.7 | 151.2 | 185.5 | 184 | 96.38 | 1220.78 |
| Odisha | 20 | – | – | – | – | 20 |
| Punjab | 90.5 | 34 | 16 | 15 | – | 155.5 |
| Rajasthan | 83.3 | 10 | 8 | 7 | – | 108.3 |
| Tamil Nadu | 532.7 | 6 | 32.6 | 31.6 | 39 | 626.9 |
| Uttarakhand | 10 | – | 20 | 20 | 13 | 50 |
| Uttar Pradesh | 644.5 | 132 | – | – | 93.5 | 842 |
| West Bengal | 16 | 10 | – | – | – | 26 |
| **Total** | **3135.33** | **465.6** | **412.5** | **405** | **400** | **4831.33** |

input energy supply (Sobek and Werle 2019; Weldekidan et al. 2019; Xie et al. 2019). Concentration solar energy is being applied to the pyrolysis reactor for converting biomass into valuable hydrocarbon (HC) fuels (Sobek and Werle 2019). Different heat energy sources such as conventional electrical energy (Kader et al. 2013; Pradhan et al. 2016; Vazquez and Barbosa 2016), microwave heat energy (Abubakar, Salema, and Ani 2013; Lam et al. 2015), and concentrated solar energy (Soria et al. 2017; Zeng et al. 2017b) could be used for pyrolysis process. Damodharan et al. demonstrated the conventional electrical energy source for the thermochemical pyrolysis process, which operated at a temperature of 500°C (Damodharan et al. 2018). Similarly, Chintala et al. (2017) utilized renewable solar energy for the pyrolysis of Jatropha seed biomass as seen in Figure 1. Production of pyro-products from biomass using concentrated solar energy depends significantly on the type of solar concentrator and design of the pyrolysis reactor. The design of a solar concentrator–pyrolysis reactor system with appropriate mechanisms and equipment is crucial for any kind of pyrolysis process. Zeng et al. utilized the concentrated solar energy for biofuel production from beech wood at a laboratory scale (Zeng et al. 2015). An innovative technology was developed by Abubakar et al. for the pyrolysis process through a microwave heating source (Figure 1) (Abubakar, Salema, and Ani 2013). Quality and yield of the pyro-oil were improved exceedingly with this new technology. In addition, the problem of bio-oil deposition in the reactor was solved with the use of microwave heating.

Recently, some investigators worked on co-pyrolysis of organic and inorganic materials for enhancing the liquid pyro-oil yield (Shah et al. 2019). Cotton stalk (organic) and waste tire (inorganic) materials were blended in different ratios as 1:0, 4:1, 3:2, 2:3, and 0:1 and pyrolyzed at

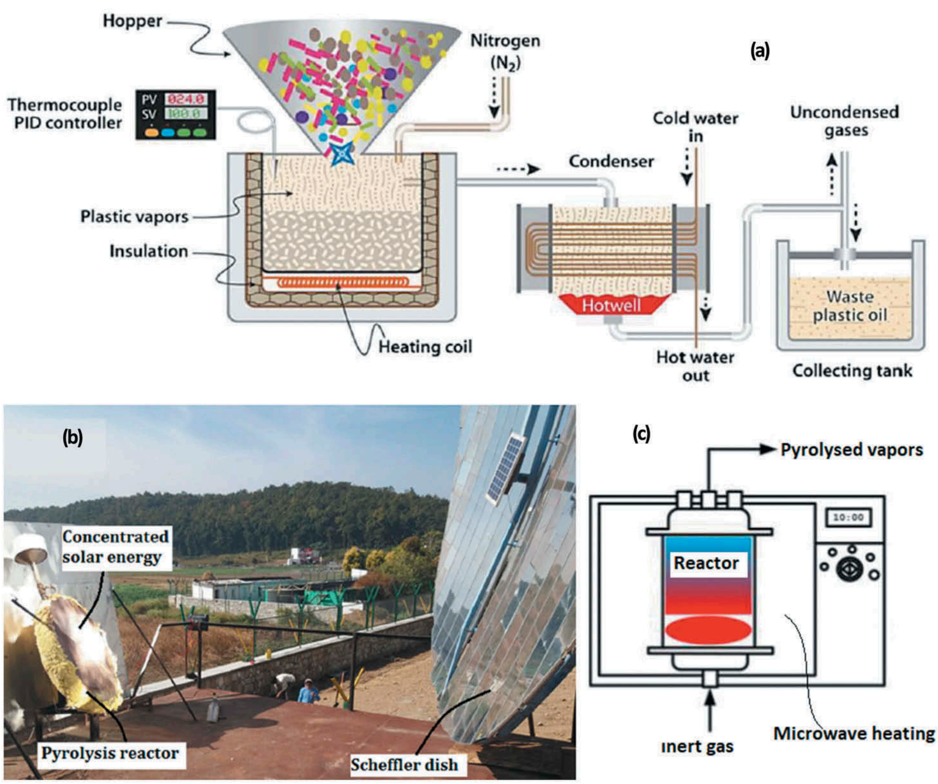


**Figure 1.** Photographic views indicating (a) electrical heating (Andrade, Barrozo, and Vieira 2018), (b) solar heating (Shah et al. 2019; Zeng et al. 2015), and (c) microwave heating (Vazquez and Barbosa 2016) sources for pyrolysis process

20°C/min heating ramp rate up to 550°C in a fixed bed reactor in the presence of nitrogen media (Shah et al. 2019). The oil yield was increased to about 78% with the co-pyrolysis technology. Similarly, different kinds of organic materials were pyrolyzed together for obtaining high oil yield with better quality. Huang et al. in their experimental investigation conducted experiments with combined feedstocks of bituminous coal and biomass in a pressurized fixed-bed pyrolysis reactor (Huang et al. 2019).

## Recent developments in the utilization of biomass-derived pyro-oils in CI engines

Pyrolysis of any kind of biomass could be carried out in fixed-bed reactors. In this process, biomass is fed into the reactor to which heat energy is supplied. When this biomass reaches a critical temperature, thermochemical reactions occur inside the reactor, which subsequently produces fuel vapors. These vapors are collected and condensed into liquid form to obtain pyro-oils (liquid product). It may be noted that some amount of vapors that are uncondensed even after effective condensation are collected separately. The condensable gases are typically termed as pyro-gas (gaseous products). After the pyrolysis reactions are completed, the leftover material inside the reactor is termed as pyro-char (solid product). Typically, pyrolyzed liquid product (pyro-oil) has higher energy density (about 24–36 MJ/kg) than a gaseous product (about 8–16 MJ/kg). Hence, the liquid product will be upgraded to petroleum fuel like, so that it could be utilized in CI engines for small-scale power generation and transport sector applications. In addition, the liquid products are storable and transportable, which is favorable for the potential source as a fuel candidate (Czernik and Bridgwater 2004). The liquid pyro-oils exhibit favorable physiochemical properties, which are suitable for engine applications (Mangesh et al. 2017). Typically, viscosity, density, and pH are measured by viscometer, density meter, and pH meter, respectively. CHN analyzer could be used for the ultimate analysis of the sample feed, i.e., to determine the elemental composition of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). Heating values of liquid fuels could be determined by a bomb calorimeter. The summary of physiochemical properties of pyro-oils derived from various biomass feedstocks is given in Table 3. Some researchers investigated the combined effect of ethanol and waste plastic pyro-oil blend on the performance and emission characteristics of a single-cylinder CI engine (Padmanabhan et al. 2017). Similarly, Vasukumar et al. also utilized waste pyro-oil and diesel blends in a CI engine (Vasukumar, Subramanyam, and Tammineni 2017). Kalargaris

**Table 3.** Literature summary on characterization parameters of pyro-oil.

| | Physico-chemical properties of bio-oils | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feedstock used | Viscosity (cSt) | Density, kg/m$^3$ | pH | C, % | H, % | N, % | O, % | HHV, MJ/kg | Flash point, °C | Pour point, °C | Water content | Ref. |
| Mahua seeds | 23.19 | 921.3 | 4.8 | – | – | – | – | 39.02 | 84 | 11 | | Pradhan et al. (2016) |
| *Chlorella vulgaris* | – | – | – | 63 | 8 | 8.5 | 20.5 | 29.8 | – | – | 1.8 | Belotti et al. (2014) |
| Rice husk | 128 | 1190 | 2.8 | – | – | – | – | – | – | – | – | Zheng et al. (2006) |
| Castor seeds | 83.19 | 960 | 3.7 | 69.3 | – | – | – | 34.9 | – | – | – | Singh and Shadangi (2011) |
| Corn stover | – | – | – | 78.0 | 9.0 | 1.8 | 10.6 | 33.8 | – | – | – | Capunitan and Capareda (2012) |
| Beech wood | – | – | – | 58.1 | 11. | 0.3 | 30.1 | 30.7 | – | – | – | Zeng et al. (2017a) |
| Softwood | | | – | 23.5 | 8.4 | 0.1 | 68.0 | 13.8 | – | – | 24.8 | Laesecke, Ellis, and Kirchen (2017) |
| Waste tire | 3.35 | 913 | | 86.9 | 10.5 | 0.6 | – | 38.1 | 49 | – | – | Sharma and Murugan (2015) |
| Sawdust | 2.6 | 850 | – | – | – | – | – | – | 68 | – | – | Tinwala et al. (2015) |
| Pine wood | 7600 | – | 3.0 | 52.1 | 6.6 | 0.5 | – | 17.12 | 84 | – | 8.1 | Yang and Wu (2017) |
| Sal seed | 1.32 | 921 | 3.7 | | | | | 23.75 | 53 | −6 | | Singh et al. (2014) |

et al. carried out a complete investigation on the effects of plastic pyro-oil use in CI engines in terms of performance, emission, and combustion characteristics (Kalargaris, Tian, and Gu 2017a, 2017b, 2017c).

It is observed from the literature that adequate investigations on utilization of pyro-oil or pyro-oil diesel blends in CI engines were reported in the literature (Chintala, Kumar, and Pandey 2017; Honnery, Ghojel, and Stamatov 2008; Hossain et al. 2013, 2016; Lee, Kim, and Kang 2013; Masimalai and Kuppusamy 2015; Murugan, Ramaswamy, and Nagarajan 2009; Pradhan et al. 2016; Prakash, Singh, and Murugan 2015, 2011; Shihadeh and Hochgreb 2000; Solantausta, Nylund, and Gust 1994; Volli, Singh, and Murugan 2014; Wongkhorsub and Chindaprasert 2013). Hence, the present study is focused on reviewing the influence of pyro-oil and diesel blends on the behavior of CI engines in terms of performance, emission, and combustion parameters.

## Influence of pyro-oils use on thermal efficiency of CI engines

Typically, heating value of fuel and its combustion performance will greatly influence the thermal efficiency of CI engines. As the pyro-oils have lower heating value than conventional fossil fuels, there could be a slight penalty in thermal efficiency with the use of pyro-oils in CI engines. Experimental results of Hossain et al. revealed a 3–7% reduction in the thermal efficiency of pyro-oil-fueled CI engine (Hossain et al. 2016). A slight penalty of 2% thermal efficiency was reported in another study on a CI engine fueled with Mahua pyro-oil (Figure 2b) (Pradhan et al. 2017). Yang et al. also reported a considerable reduction in the thermal efficiency of a CI engine fueled with coffee bean residue pyro-oil (Yang et al. 2014). Similarly, results of many other investigations are also in line with fact of slight reduction in thermal efficiency of pyro-oil-fueled CI engines (Chiaramontia et al. 2003; Lee, Kim, and Kang 2013; Pradhan et al. 2017; Prakash, Singh, and Murugan 2011; Volli, Singh, and Murugan 2014; Wongkhorsub and Chindaprasert 2013). In contrast to this, a few

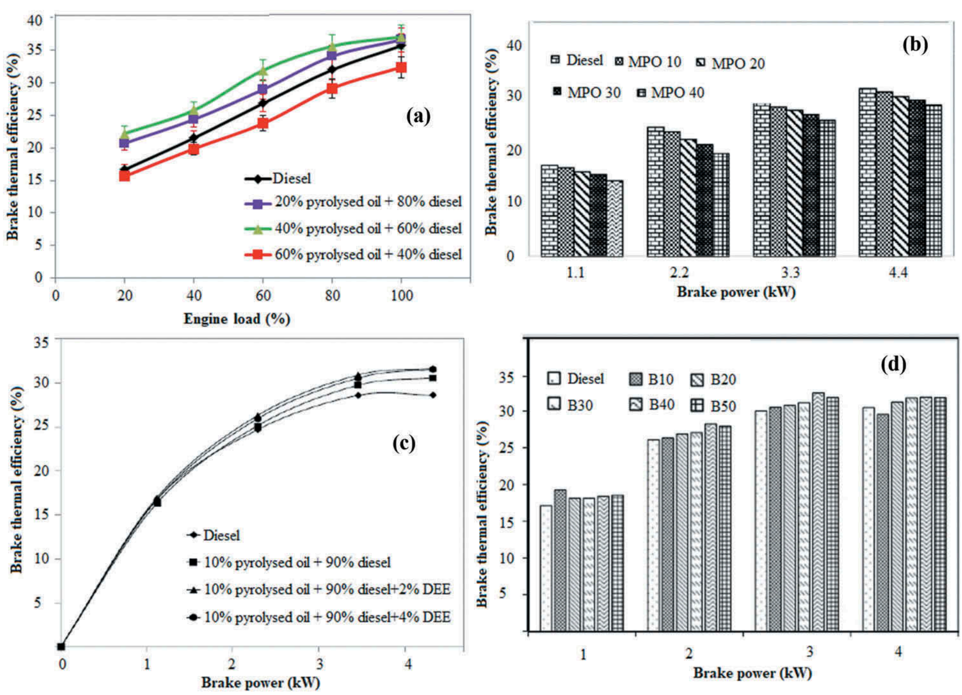


Figure 2. Brake thermal efficiency variation with different pyro-oil–diesel blends: (a) Chintala et al. (Shah et al. 2019), (b) Pradhan et al. (Honnery, Ghojel, and Stamatov 2008), (c) Prakash et al. (Wongkhorsub and Chindaprasert 2013), and (d) Volli et al. (Hossain et al. 2016).

investigations reported a slight increase in the thermal efficiency of pyro-oil-fueled CI engines. For example, Volli et al. found 4.7% increment with mustard cake pyro-oil (30%)–diesel-blended fuel as compared to neat diesel fuel operation. Figure 2d reports a slight increase in the efficiency with increasing pyro-oil share from 10 to 50%, i.e., B10–B50 (shown in Figure 2d; Volli, Singh, and Murugan 2014). Similarly, Prakash et al. reported a slight increase in the thermal efficiency of a CI engine fueled with wood pyro-oil–diesel fuel blends (Prakash, Singh, and Murugan 2015). However, with all aforementioned inferences, it may be concluded that with consideration of uncertainty in experimentation and measurements, the efficiency of CI engines with pyro-oils is almost comparable with diesel fuel operation.

## Influence of pyro-oil use on hydrocarbon and carbon monoxide emissions

The major pollutants from CI engines are typically HC, carbon monoxide (CO), oxides of nitrogen ($NO_x$), smoke, and carbon dioxide. Figure 3 demonstrates the comparison of HC and CO emissions in CI engines operated with pyro-oil–diesel-blended fuels. It is explored from the literature that HC and CO emissions decrease significantly with pyro-oil-blended fuels. For example, Prakash et al. found about 36% reduction in HC emission with 15% wood pyro-oil (Prakash, Singh, and Murugan 2015). Hossain et al. also found 39% and 66% reductions in CO emissions with the use of 20% and 30% pyro-oil (Hossain et al. 2016). Other investigations also reported similar kind of results of reduction in HC and CO emissions for a lower percentage of pyro-oil blending than a higher percentage of blending (Figure 3a–d). For example, Chintala et al. found an initial reduction in HC and CO emissions up to 40% Jatropha pyro-oil share and then increased slightly with 60% pyro-oil share as shown in Figure 3a,b. The main reasons for the reduction in the emissions could be the presence of inherent oxygen content in the pyro-oil, which helps in better oxidation reactions inside the combustion chamber. Volli et al. also reported a fluctuating trend with an increasing share of mustard cake pyro-oil share (beyond 30%, Figure 3c,d; Volli, Singh, and Murugan 2014). Experimental investigations of Pradhan et al. also confirmed the trend of continuous increase in HC and CO emissions with increasing Mahua pyro-oil share from 10 to 40% (shown in Figure 3e,f). It could be attributed mainly due to a higher percentage of pyro-oil that causes misfiring and poor combustion performance. With an increasing pyro-oil share, the heating value of blended fuel will decrease significantly, which may lead to poor combustion performance. The main reasons could be improper air–fuel mixing of fuel that resulted in incomplete combustion reactions. In addition, higher viscosity of pyro-oil–diesel blend led to poor fuel spray characteristics, i.e., long spray penetration, large fuel droplets, and poor atomization, which subsequently caused air–fuel mixing problems and thus incomplete combustion (Pradhan et al. 2017).

## Influence of pyro-oil use on oxides of nitrogen and smoke emissions

$NO_x$ pollutant formation mainly depends on three significant parameters: (i) oxidation reaction temperature, (ii) oxygen content during the combustion reaction, and (iii) reaction time (Chintala and Subramanian 2017, 2016; Stone 1999; Turns 2000). A fluctuating trend of $NO_x$ emission was reported by Chintala et al. with an increasing share of pyro-oil as demonstrated in Figure 4a (Chintala, Kumar, and Pandey 2017). The pollutant formation rate increased until 40% of the pyro-oil share and then declined with further increasing oil share in the fuel blends (Ansari and Gaikar 2019). Similarly, Masimalai and Kuppusamy also reported a slight reduction in $NO_x$ emission with pyro-oils derived from a variety of biomass feedstocks such as *Prosopis juliflora* seeds, Kiker seeds, and coconut shells (Masimalai and Kuppusamy 2015). This decreasing trend was observed even with a lower percentage of pyro-oils by some other researchers also. For example, Pradhan et al. found the $NO_x$ emission reduction from 3 g/kWh with 10% pyro-oil to about 2 g/kWh with a 40% pyro-oil share as seen in Figure 4c (Pradhan et al. 2017). With the increasing share of Mahua pyro-oil, the $NO_x$ emission decreased from 4.5 to 2.8% at all engine loads (Pradhan et al. 2017). The main reason for the reduction

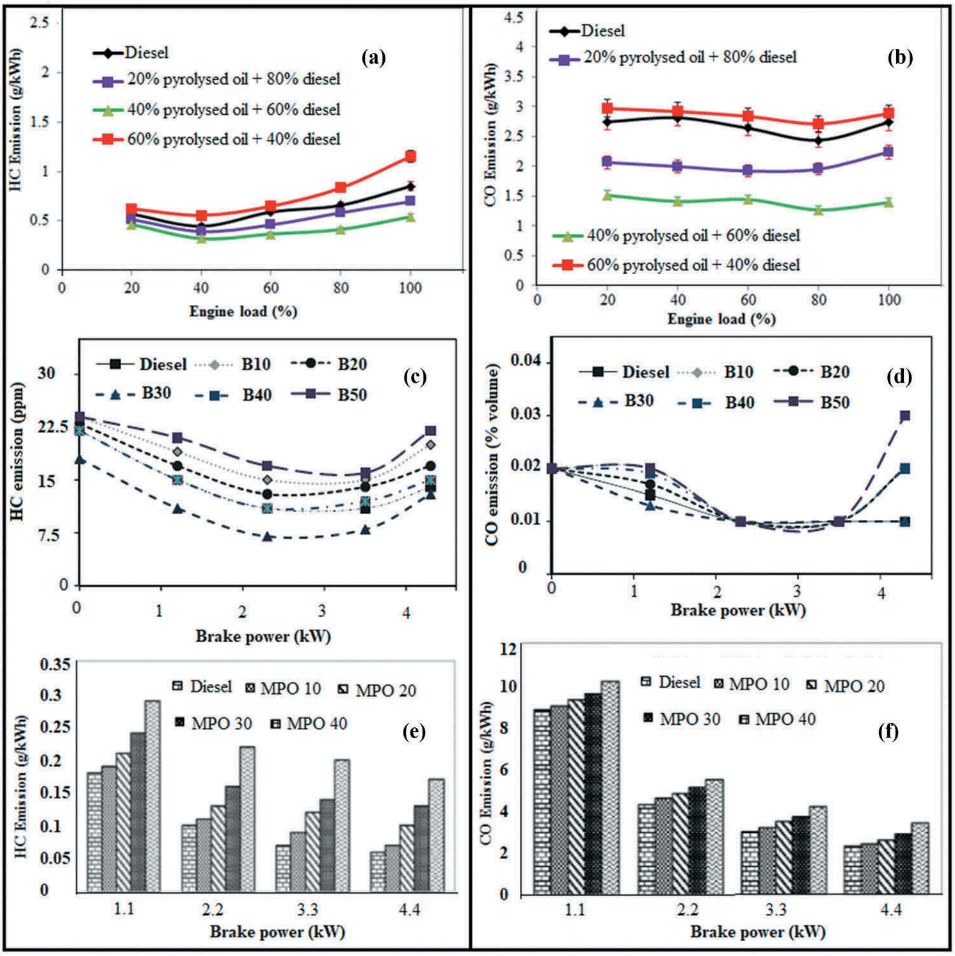


**Figure 3.** Hydrocarbon and carbon monoxide emission variations with respect to pyro-oil blending share: (a,b) Chintala et al. (Shah et al. 2019), (c,d) Volli et al. (Hossain et al. 2016), and (e,f) Pradhan et al. (Honnery, Ghojel, and Stamatov 2008).

could be lower in-cylinder temperature (Kusumo et al. 2017; Silitonga et al. 2018). Similarly, Yang et al. also found the emission reduction with an increasing share of coffee bean residue pyro-oil in an 11.8-kW CI engine (Yang et al. 2014). Higher oxygen content present in pyro-oils and higher combustion temperature may cause the emission formation at higher rates. However, with a 60% pyro-oil share, the emission decrease may be due to the corresponding reduction in in-cylinder temperature (Figure 4a) (Chintala, Kumar, and Pandey 2017).

It is well accepted that the smoke formation rate significantly depends on the heterogeneous combustion inside the engine cylinder. With a higher percentage of pyro-oil blending in diesel fuel, the degree of heterogeneous combustion increases and thus emission formation increases correspondingly. However, with a lower percentage of pyro-oils, the heterogeneity of air–fuel mixture may not affect the emission formation. Smoke emission results of both the works (Chintala et al. and Pradhan et al.) agree as observed in Figure 4b,d. Smoke emission formation rate was decreased by about 28% with 15% pyro-oil as shown in Figure 4 (Prakash, Singh, and Murugan 2015). With other kinds of biomass-derived pyro-oils (*Prosopis juliflora* seeds, Kiker seeds, and coconut shells) also, the emission was decreased significantly (Masimalai and Kuppusamy 2015). Chintala et al. reported about 10% reduction with 40% pyro-oil share and then it increased, whereas Pradhan et al. found the emission reduction until 30% pyro-

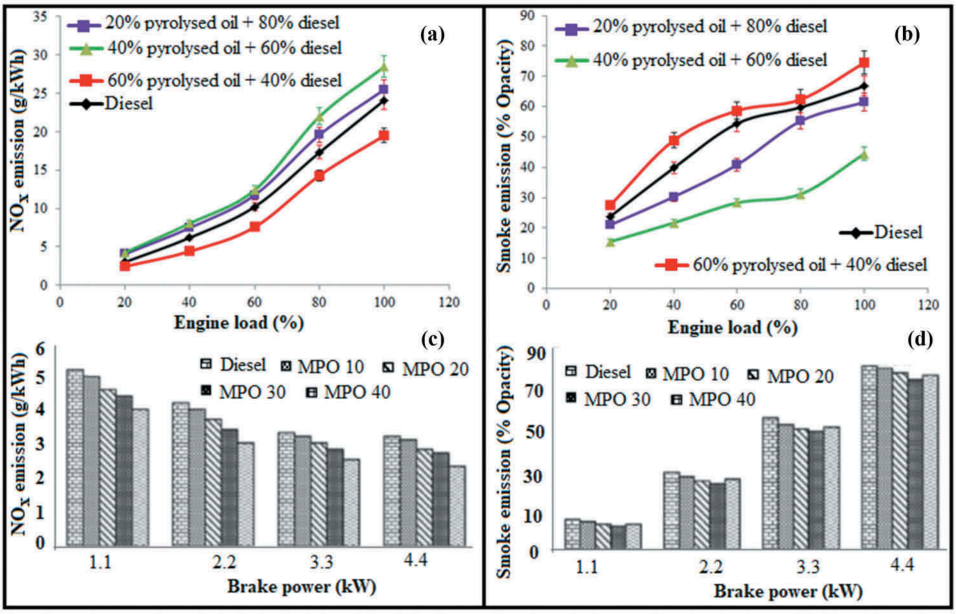


Figure 4. $NO_x$ and smoke emission variations with respect to pyro-oil blending share: (a,b) Chintala et al. (Shah et al. 2019) and (c,d) Pradhan et al. (Honnery, Ghojel, and Stamatov 2008).

oil share followed by a slight increase as demonstrated in Figure 4b,d. Yang et al. also support the smoke emission increase with a higher percentage of pyro-oil use in a CI engine due to reduced heating values and combustion efficiency (Yang et al. 2014).

## Influence of pyro-oil use on combustion parameters of CI engines

With the use of pyro-oil–diesel blends in a CI engine, typically in-cylinder pressure decreases as compared to neat diesel fuel operation. The percentage of the pressure reduction is higher at high shares of pyro-oil at all loads. The work of Chintala et al. (Figure 5) reveals that the in-cylinder pressure increased initially with 20% pyro-oil shares at all engine loading conditions (Chintala, Kumar, and Pandey 2017). However, this pressure decreased significantly with the use of 40% and 60% pyro-oil shares in the blend as seen in Figure 5. At lower pyro-oil shares, the peak pressure increased considerably from 66.5 to 71.4 bars (Figure 5). It could be interpreted that the inherent oxygen content in the pyro-oil enabled better combustion efficiency; however, with higher pyro-oil shares, poor atomization of fuel particles and improper air–fuel mixing could have occurred, due to which the peak pressure decreased. Pradhan et al. (2017) and Hossain et al. (2016) also reported the similar kinds of trends with pyro-oil-blended fuel use in CI engines. The peak pressure was about 70 bar with the pyrolyzed oil–blended diesel as seen in the figure (Hossain et al. 2016). They reported that the main reason for higher in-cylinder was improved combustion performance. However, with 40% pyro-oil share, the peak pressure decreased significantly to about 60 bar (Pradhan et al. 2017). The heat release rate also increased with the increasing share of pyro-oil as evident in Figure 6. The maximum heat release was varied with reference to the engine configuration used for the experiments by various researchers. For example, Pradhan et al. reported that the maximum heat release was about 65 J/degree CA, whereas Hassan et al. reported as 30 J/degree CA as seen in the figure. Combustion was delayed with the increasing share of Jatropha pyro-oil in the blend (Figure 6). With the addition of high amounts of pyro-oil in the blend, the fuel spray characteristics (spray penetration, Sauter mean diameter of fuel droplets, and atomization) deteriorate as the density and viscosity

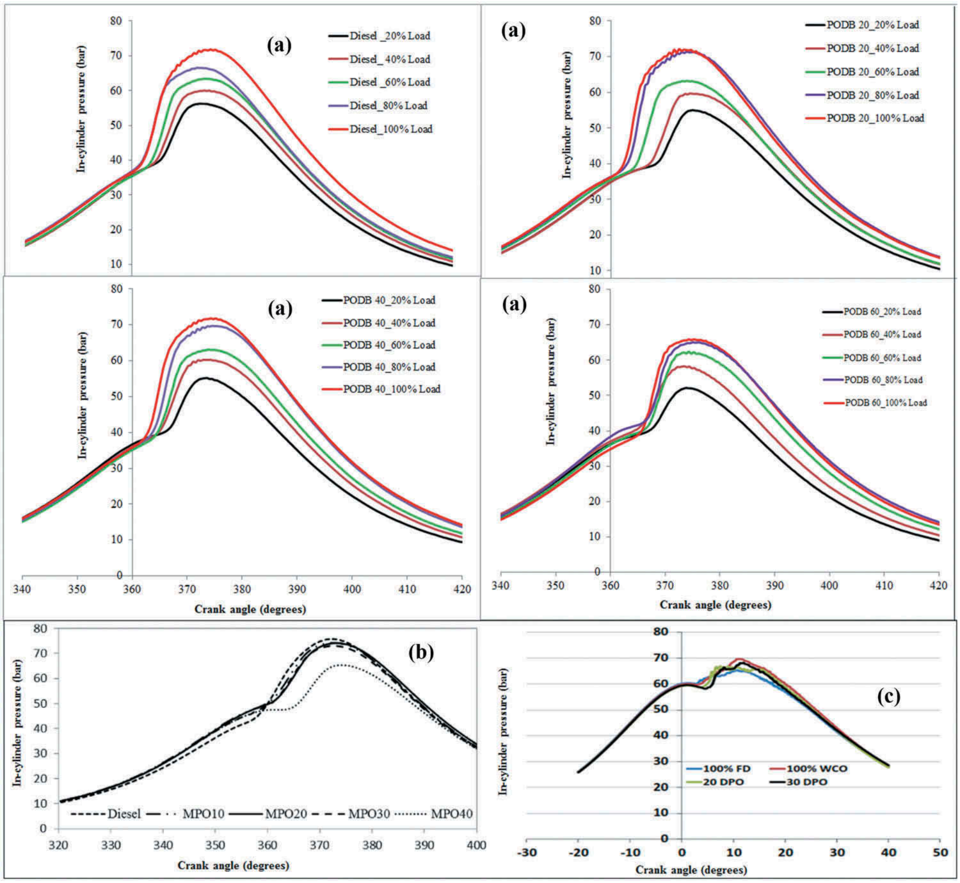


Figure 5. In-cylinder pressure variation with respect to increasing pyro-oil share: (a) Chintala et al. (Chintala, Kumar, and Pandey 2017), (b) Pradhan et al. (Pradhan et al. 2017), and (c) Hossain et al. (Hossain et al. 2016).

of the fuel increase (Heywood 1988; Subramanian and Chintala 2013). This further leads to heterogeneous air–fuel mixture formation and poor preignition chemical reactions, which finally result in delayed combustion as shown in Figure 6 (Chintala, Kumar, and Pandey 2017). This phenomenon of delayed combustion is also reported in some other studies carried out on the use of pyro-oil in CI engines (Pradhan et al. 2017; Shihadeh and Hochgreb 2000).

## Challenges and recommendations for future research on biomass-derived pyro-oil utilization in engines

Biomass-derived pyro-oils are typically mixed with char materials, which are difficult to remove 100% from the oils. The presence of char particles of very smaller sizes, i.e., less than 2 mm, would create clogging problems in the entire fuel supply line system (Lee, Kim, and Kang 2013). The main fuel line components such as pump, filter, and injector would suffer the clogging problem due to the presence of heavier particles of biochar in the pyro-oils. Experimental works carried out by the present study authors (Chintala et al.) and Lee at al. revealed the problem of clogging in fuel filter element and fuel injector as seen in Figure 7a–c. Chintala et al. operated a direct injection CI engine with Jatropha seed–derived pyro-oil–diesel blends (20%, 40%, and 60% pyro-oil blended with diesel) and found clogging of fuel line system because of which engine starting problem was encountered (Figure 7c). This problem was still severe with a high

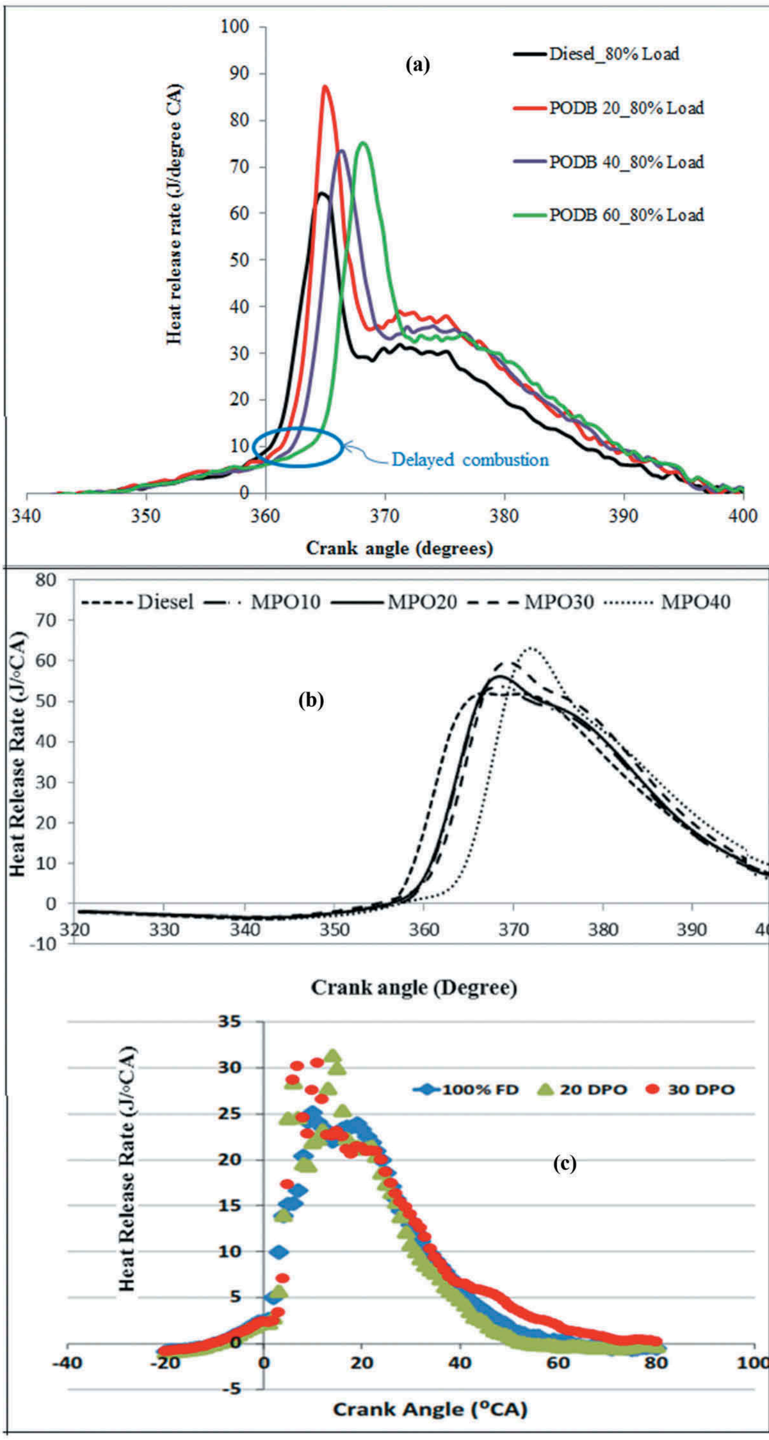


Figure 6. Identification of combustion delay with increasing pyro-oil share: (a) Chintala et al. (Chintala, Kumar, and Pandey 2017), (b) Pradhan et al. (Pradhan et al. 2017), and (c) Hossain et al. (Hossain et al. 2016).

percentage of pyro-oil blends (beyond 40% share) (Chintala, Kumar, and Pandey 2017). Lee et al. worked with wood-based pyro-oil diesel blends on a CI engine (Lee, Kim, and Kang 2013). As they had used a 4-mm filter element, the char particles of lesser than 4 mm were unable to be

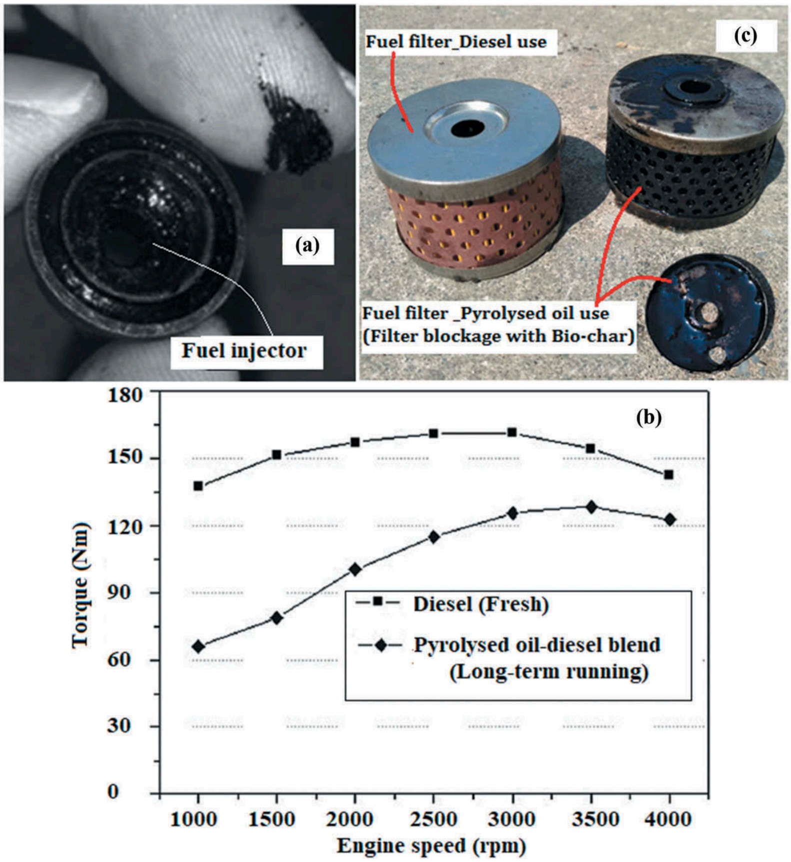


**Figure 7.** Long-term running problems for engine fuel line elements: (a,b) fuel injector clogging (Masimalai and Kuppusamy 2015) and (c) fuel filter element clogging (Shah et al. 2019).

filtered out and thus caused blockage of fuel injector holes (Figure 7a). Pyro-oil droplets smaller than 4 mm were passed through the filter element and thus later joined together to form larger droplets through polymerization (Lee, Kim, and Kang 2013). As the fuel injector needle lift/movement is optimized with reference to the conventional diesel fuel, clogging of char particles in the injector needle will create serious problems of fuel spray characteristics (fuel spray length, droplet diameter, atomization of fuel droplets, vaporization, and mixing of fuel droplets with air), and the fuel supply system will not perform properly. It is evident from Figure 7c that the torque output of the engine was reduced significantly with long-term operation of pyro-oil–diesel blends. This effect was quite severe at lower engine speeds. At lower speeds, i.e., 1000 and 1500 rpm, engine torque was reduced by 50% as seen in Figure 7c. The main reason for the torque reduction was due to burnout carbon particle deposits in the injector's needle during the combustion. Even after the combustion of char particles that were entrained into the combustion chamber, formation of tar occurs, which would create problems in the engine components. In order to prevent this problem, lower shares of pyro-oil could be blended with diesel. This was confirmed by the authors with the earlier experimental results, i.e., 40% pyro-oil (PO40: 40% pyro-oil + 60% diesel) was selected as an optimum blend for better performance and lower emission characteristics of the engine (Chintala, Kumar, and Pandey 2017). If the pyro-oil-diesel blends are used for engine's long-run operation, the fuel supply system may be rinsed with alcohol fuels for cleaning up the fuel line components (fuel pump, filter, and injector elements) at regular intervals. Based on these inferences, it is concluded that the long-term performance of the engine is a serious concern for the effective utilization of biomass-derived pyro-oils in CI engines.

## Conclusions

The state of the art on the utilization of pyro-oils in CI engines has been reviewed and derived into conclusions which are as follows:

- A wide variety of biomass feedstocks such as Jatropha seeds, beech wood, date seeds, and agriculture and forestry residues are potential feedstock candidates for the production of biofuels, i.e., pyro-oil, pyro-gas, and biochar via solar pyrolysis process.
- With the use of pyro-oils in CI engines, the thermal efficiency of the engines decreases slightly due to a slight reduction in heating value and poor combustion performance. However, with consideration of error limits, the thermal efficiency of the engine with pyro-oils may be comparable with conventional diesel fuels.
- HC, CO, and smoke emissions from CI engines decrease slightly with the use of pyro-oils. However, a slight penalty in $NO_x$ emissions was observed with pyro-oil usage in the engines.
- Heat release rate slightly increases with pyro-oil application in engines due to inherent oxygen content in the fuels.
- Some studies highlighted the problems associated with engine fuel line systems due to carbon deposits produced by the combustion of biomass-derived pyro-oils.

As the problem of fuel element clogging limits the effective use of pyro-oils in CI engines, it is suggested that biomass-derived pyro-oils need to be upgraded for its effective use in the engines.

## Abbreviations

| | |
|---|---|
| BTE | Brake thermal efficiency |
| CI | Compression ignition |
| CO | Carbon monoxide emission |
| HC | Hydrocarbon emission |
| MPO | Mahua seeds–derived pyro-oil |
| N | Engine speed, rpm |
| $NO_x$ | Oxides of nitrogen emission |
| P | Brake power |
| PO | Pyro-oil |
| PODB | Pyro-oil diesel blend |

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