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Combustion of fuel blends containing digestate pyrolysis oil in a multi-cylinder compression ignition engine

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HIGHLIGHTS

- Digestate from anaerobic digestion plant was converted into pyrolysis oil.
- The oil was blended with waste cooking oil and butanol and tested in a diesel engine.
- Thermal efficiency decreased by 3–7%, combustion duration decreased by 3–12%.
- Peak cylinder pressures decreased by 2–4%, ignition delay increased.
- Blends gave lower smoke levels, similar CO_2 emissions.

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ABSTRACT

Digestate from the anaerobic digestion conversion process is widely used as a farm land fertiliser. This study proposes an alternative use as a source of energy. Dried digestate was pyrolysed and the resulting oil was blended with waste cooking oil and butanol (10, 20 and 30 vol.%). The physical and chemical properties of the pyrolysis oil blends were measured and compared with pure fossil diesel and waste cooking oil. The blends were tested in a multi-cylinder indirect injection compression ignition engine. Engine combustion, exhaust gas emissions and performance parameters were measured and compared with pure fossil diesel operation. The ASTM copper corrosion values for 20% and 30% pyrolysis blends were 2c, compared to 1b for fossil diesel. The kinematic viscosities of the blends at 40 °C were 5–7 times higher than that of fossil diesel. Digested pyrolysis oil blends produced lower in-cylinder peak pressures than fossil diesel and waste cooking oil operation. The maximum heat release rates of the blends were approximately 8% higher than with fossil diesel. The ignition delay periods of the blends were higher; pyrolysis oil blends started to combust late and once combustion started burnt quicker than fossil diesel. The total burning duration of the 20% and 30% blends were decreased by 12% and 3% compared to fossil diesel. At full engine load, the brake thermal efficiencies of the blends were decreased by about 3–7% when compared to fossil diesel. The pyrolysis blends gave lower smoke levels; at full engine load, smoke level of the 20% blend was 44% lower than fossil diesel. In comparison to fossil diesel and at full load, the brake specific fuel consumption (wt.) of the 30% and 20% blends were approximately 32% and 15% higher. At full engine load, the CO emission of the 20% and 30% blends were decreased by 39% and 66% with respect to the fossil diesel. Blends CO_2 emissions were similar to that of fossil diesel; at full engine load, 30% blend produced approximately 5% higher CO_2 emission than fossil diesel. The study concludes that on the basis of short term engine experiment up to 30% blend of pyrolysis oil from digestate of arable crops can be used in a compression ignition engine.

1. Introduction

In 2012, about 10% of the total world greenhouse gas emission came from the European Union [1]. Recently, the EU parliament has set a 2030 target of at least: (i) 40% emission reduction compared to 1990 level, (ii) 27% energy share from renewables, and (iii) increasing energy efficiency by 27% [2]. Increased use of renewable biofuels, and energy recovery from waste streams from bioenergy conversion, would help to achieve the EU's 2030 target.

Anaerobic digestion (AD) is a well-known conversion process yielding biogas from organic biomass materials. The waste stream

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form the anaerobic digestion plant (known as digestate or slurry) contains soil nutrients (notably N, P and K). In the UK alone, AD plants generates approximately 277,000 tonnes/year of digestate [3]. The digestate is widely used as a fertiliser in farm land to release these soil nutrients [4,5]. However, the effectiveness of the digestate as fertiliser will depend on the type of biomass feedstock and processing parameters used. There is a concern about land spreading of digestate due to the possible heavy metals and pathogen content if not controlled properly [6–8]. Alternative uses of digestate have been investigated by several researchers [9–16]. A simulation study was carried out to study the feasibility of using the digestate sludge for incineration in a steam turbine plant [9]. It was reported that integrated AD-steam cycle system could meet up to 13–18% of the electricity demand of the whole AD plant. The authors mentioned that reducing the digestion period would enhance the quality of digestate and hence electricity production; but on the other hand, this would affect the production of biogas [9]. Besides incineration, pyrolysis and gasification of the AD digestate (and sludge) has also been investigated [14,15]. Troy et al. [14] investigated the quality of pyrolysis fuel products using a blend of saw dust and pig manure digestate as feedstock. The authors reported that addition of saw dust increased the net energy yield from biochar. Yue et al. [16] reported that 6.3 m^3 of ethanol can be produced from 0.6 tonne of dry digestate fibre (obtained from 1 tonne of cattle manure used in the AD plant).

Pyrolysis can convert biomass and waste into liquid, solid and gaseous forms. All three fractions have potential as fuels in various types of prime mover for transport, power generation, and combined heat and power application. In this study, pyrolysis oil (organic liquid fraction) produced from anaerobically digested pellets will be examined as a fuel for diesel engine applications. Recent research highlighted the potential of pyrolysis oils as renewable biofuels for internal combustion (IC) engine applications [17,18]. However, due to their low energy content, high acidity and viscosity, upgrade is required prior to use. One upgrade method is to blend pyrolysis oil with another component e.g. with biodiesel (or diesel) or other biofuels [19–24]. Among the various pyrolysis techniques, intermediate pyrolysis attracted attention due to the flexibility of the feedstock used (can process biomass with ash content as high as 30%) [25–27]. Recent studies showed that intermediate pyrolysis oils (produced from feedstocks such as de-inking sludge and sewage sludge) blended with biodiesel could be a potential fuel for diesel engine applications [28,29]. Butanol acts as a good co-solvent for blending; stable single phase blends are produced when bio-oil, biodiesel and butanol are mixed [30]. Currently, butanol is being produced mainly from petrochemical resources; but bio-butanol can be produced from biomass resources via fermentation [31–33].

In a typical AD plant about 33–50% of the feedstock energy is converted into biogas [34,35]. This means more than half of the feedstock energy remains in the digestate, making it a very promising feedstock for production of biofuel via, for example, the intermediate pyrolysis technique. Although researchers investigated the use of pyrolysis oils produced from various biomass resources, hardly any study was found on the use of digestate pyrolysis oil (DPO). The aim of the current study is to investigate the combustion and emission performance of digestate pyrolysis oil blends in a multi-cylinder indirect injection compression ignition engine. The objectives of the study were to: (i) produce and characterise intermediate pyrolysis oil from digestate, (ii) investigate and prepare stable pyrolysis oil blends, (iii) characterise pyrolysis oil blends, (iv) analyse combustion, performance and exhaust emissions characteristics of the pyrolysis oil blends used in the engine. In the present study, digestate pyrolysis oil was blended successfully with waste cooking oil (WCO) and butanol (BL) in various proportions. The physical and chemical properties of the digestate pyrolysis oil and blends were measured. The digestate pyrolysis oil blends were tested in a multi-cylinder indirect injection diesel engine. Engine combustion, performance and emission parameters were measured and analysed; these results were compared with the standard fossil diesel (FD) operation.

Table 1
Properties of the digestate pellets from anaerobic digestion of maize and green rye.

Proximate analysis	
Moisture content (wt.%)	11.5
Ash content (wt.%, dry basis)	35.7
Volatile matter (wt.%, dry basis)	54.1
Proximate analysis (wt.%, dry basis)	
Carbon	35.95
Hydrogen	3.91
Nitrogen	3.54
Chlorine	0.87
High heating value (MJ/kg)	15.02

2. Materials and methods

2.1. Anaerobic digestion and digestate pellets

Anaerobic digestion produces two main products: digestate and biogas. The digestate used in this study comes from MeMon BV, a Dutch company, where the material from the anaerobic digestion of arable crops (maize and green rye) was dried and pelletised.

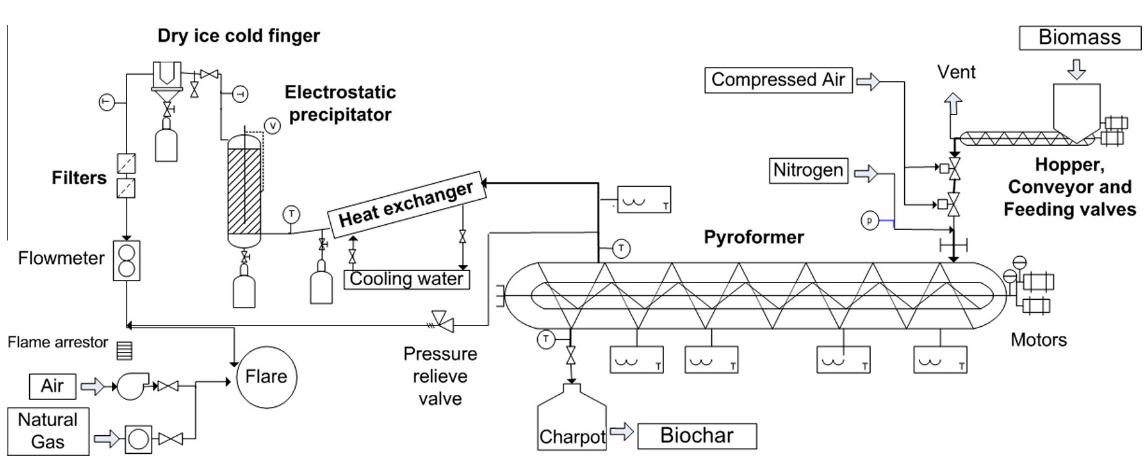

Fig. 1. Intermediate pyrolysis (Pyroformer®) – reactor and accessories.