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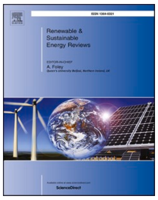

Bioliquids and their use in power generation – A technology review

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ABSTRACT

The first EU Renewable Energy Directive (RED) served as an effective push for world-wide research efforts on biofuels and bioliquids, i.e. liquid fuels for energy purposes other than for transport, including electricity, heating, and cooling, which are produced from biomass. In December 2018 the new RED II was published in the Official Journal of the European Union. Therefore, it is now the right time to provide a comprehensive overview of achievements and practices that were developed within the current perspective. To comply with this objective, the present study focuses on a comprehensive and systematic technical evaluation of all key aspects of the different distributed energy generation pathways using bioliquids in reciprocating engines and micro gas turbines that were overseen by these EU actions. Methodologically, the study originates from the analyses of feedstock and fuel processing technologies, which decisively influence fuel properties. The study systematically and holistically highlights the utilisation of these bioliquids in terms of fuel property specific challenges, required engine adaptations, and equipment durability, culminating in analyses of engine performance and emissions. In addition, innovative proposals and future opportunities for further technical improvements in the whole production-consumption cycle are presented, thus serving as a guideline for upcoming research and development activities in the fast-growing area of bioliquids. Additionally, the paper systematically addresses opportunities for the utilisation of waste streams, emerging from the ever increasing circular use of materials and resources. With this, the present review provides the sorely needed link between past efforts, oriented towards the exploitation of bio-based resources for power generation, and the very recent zero-waste oriented society that will require a realistic exploitation plan for residuals originating from intensive material looping.

1. Introduction

The first EU Renewable Energy Directive (RED) [1] stimulated fundamental and applied research in combination with industrial investigations on biofuels and bioliquids, thus enabling their applications in several different industrial sectors. The Directive set the ambitious target of 20% of renewable energy sources (RES) within final energy use by 2025, aiming to reduce CO_2 emissions and to fulfil the Paris agreement. In December 2018, the new RED II was published in the Official Journal of the European Union [2] to raise RES up to 32% by 2030. Although some gaps are still to be filled in RED II, it is worth noting that fuels derived from waste are expected to play a major role in the European global agenda for the first time [2], also leading to potential side streams of chemical energy bearing liquids, which show some similarities to bioliquids. Moreover, RED II pushes for low indirect land use change (ILUC) risk feedstock for bioliquid or biofuel production, generating a growing interest for bioliquids produced from alternative feedstock.

Regarding the many RES defined within RED, the present paper focuses on one particular group, which has been also clearly defined within RED II, i.e. bioliquids. Bioliquids are defined as "*liquid fuels for energy purposes other than for transport, including electricity, heating and cooling, produced from biomass*" [2]. Interestingly, the general public tends to confuse this bio-source with biofuels. However, the difference between biofuels and bioliquids is significant. For the first case (transport) the fuel must be upgraded to the specifications defined in the applicable norms and standards for use in engines and for the entire

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Abbreviations

RES –	Renewable Energy Sources
RED –	Renewable Energy Directive
ILUC	Indirect Land Use Change
FPBO –	Fast Pyrolysis Bio-Oil
HTL –	Hydrothermal Liquefaction
GHG –	Greenhouse Gas
CEN –	European Committee for Standardization
GWP –	Global Warming Potential
pTSA –	para Toluensulfonic Acid
ICE –	Internal Combustion Engine
GT –	Gas Turbine
MGT –	Micro Gas Turbine
CHP –	Combined Heat and Power
APU –	Auxiliary Power Unit
FAME –	Fatty Acid Methyl Ester
OEM	Original Equipment Manufacturer
LHV –	Lower Heating Value
D2 –	No. 2 Fuel Oil
EtOH –	Ethanol
PM –	Particulate Mass
TRL –	Technology Readiness Level

logistic chain (i.e. transport, storage, etc.), while for the second case (stationary energy generation) the technology can be adapted to meet the fuel characteristics. Therefore, bioliquids can be raw liquids, biocrude, and intermediate energy carriers that can be employed in technologies specifically modified to the fuel properties, whereas biofuels are roughly following a drop-in approach and do not require specifically modified power generation technologies for their exploitation. Fig. 1 presents how bioliquids are positioned among other biomass-derived energy carriers.

Particular to this work, the motivation to focus on bioliquids arises from the fact that RED II includes the same feedstock category for the group of the biointermediate energy carriers, which play a significant role in supporting the transition to a circular economy. The concept of biointermediate energy carries or bioliquids (if they are used for energy purposes in their liquid form), could cover a large spectrum of initial biomass including residual agro-waste or waste streams, thus favouring power generation and grid balancing by following the cascade and circular approach of biomass use.

Bioliquids often exhibit challenging physical and chemical characteristics due to their intrinsic, extensive biobased resource cascade and conversion of waste streams, thus leading to their conversion to energy carriers, which would hardly be upgraded to meet the strict limitations for biofuels. In this context, it is also worth noting that variations in feedstock quality and circular production processes among industries will likely result in side-products with great variations of properties, leading to specific requirements for designing and adapting distributed power generation techniques to specific applications.

To properly evaluate the advances of bioliquids in recent years and to identify their possible role and potential application in future power generation systems, a comprehensive overview of the achievements and practices that were developed within the current perspective (RED) is necessary. In this way, the present work focuses on a comprehensive technical evaluation of all key aspects of different energy generation pathways which use bioliquids as energy carriers. The adequate approach to such a challenge is to take into account the complete conversion path from bioliquids to power with a particular emphasis on two key conversion steps:

- The processes for the production of bioliquids, aiming to identify their potential by critically evaluating the suitable feedstock with opportunities to implement them into circular economy guidelines. Strong points for fostering the use of bioliquids, as well as current challenges and barriers that constrain the potential of large scale implementation will be addressed in parallel.

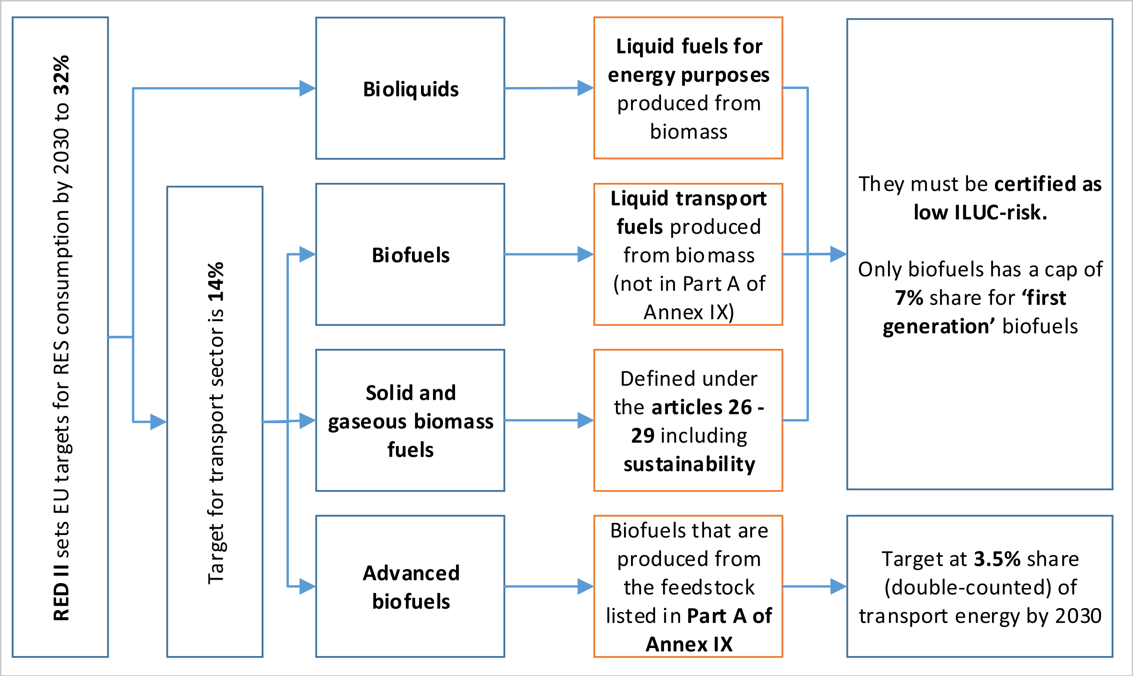

Fig. 1. The positioning of bioliquids among biomass-derived energy carriers.

- Suitable power generation systems for the utilisation of bioliquids, together with their environmental performance, will be analysed to provide a series of developed technical solutions. Proposals for improvement and the applicability to current power generation systems will be given along with best practices and guidelines for future improvements in terms of fuel flexibility and power demand. By focusing on distributed power generation techniques, reciprocating engines and micro gas turbines will be emphasized.

Although the literature survey revealed a limited number of review papers where a single bioliquid is investigated or the investigation of bioliquids is mixed with biofuels (for example, pyrolysis oils [3,4], pyrolysis oil, liquefied biomass and biodiesel [5], higher alcohols [6], and others), a majority of original research studies is dispersed in a large scientific field, hence limiting the transferability of solutions and comparability of data between them. The present review is therefore largely based on the original research that was performed in the last decade which corresponds to the validity of RED, however the most important enabling technical solutions developed before this period are presented as well.

The paper is divided into five sections. Section 2 provides overview of the key feedstock, process parameters, and physical and chemical properties of key bioliquids is given that serves as a basis for evaluating the interaction of bioliquids with power generation systems. Section 3 in-detail analyses research experience, challenges, and advances in the area of power generation systems that utilise bioliquids by addressing and comprehensively evaluating key components, performance, emissions, as well as the required system adaptations. Section 4 is devoted to the critical assessment and interlinking of technical advances done on power generation systems, and their technical viability for power generation with bioliquids. It particularly targets future-proof applications, and the possibilities to support the transition to a circular economy by identifying the role of power generation with bioliquids in emerging waste streams, while at the same time identifying and discussing the research questions that remain open. Finally, Section 5 envelopes the key findings and contributions, which position the review within energy development strategies of the next decade.

The elements of the paper thus, for the first time, comprehensively cover a systematic and insightful analysis of power generation with bioliquids and the accompanying technology advances that form a basis to support an efficient uptake of the newly introduced RED II. The review is further establishing a link between bioliquids and an ever increasing portfolio of novel bio-based processes. These processes yield an interesting set of waste streams with a high potential to benefit from further technical advances in power generation systems designed for the use of bioliquids. The identified opportunities to intertwine these improvements with emerging waste streams present a large potential to further increase the viability of bioliquids within future strategies in the area of circular economy, hence also giving the review permanent value in the accompanying areas covering sustainable development.

2. Assessment of available bioliquids

As liquid fuels made from biomass which are used for energy purposes other than transport, bioliquids can include a broad spectrum of biocrudes and intermediate energy carriers.

Biocrudes are often produced via the thermochemical processing of biomass, i.e. they essentially consist of oxygenated substitutes of crude oils [7]. However, bioliquids may also include lipid based feedstock such as straight vegetable oils, fatty acids, and waste lipids (i.e. used cooking oils, tanning and food waste), that could be either directly used in stationary heat and power applications, upgraded to conventional biofuels [8], or advanced renewable transport fuels [9]. In order to strictly follow the definition of bioliquids, the review focuses on the following subtypes:

- Fast pyrolysis bio-oils (FPBO)
- Hydrothermal liquefaction biocrude (HTL biocrude)
- Liquefied wood
- Straight vegetable oils (SVO)
- Bioalcohols

While biofuels are deliberately omitted in the paper, since their use is justifiable almost exclusively in transport applications, two groups of biofuels will be addressed in combination with bioliquids, as they play an important role in the bioliquid utilisation and production: Alcohol fuels – such as ethanol, glycerol, and biodiesel. These are often exploited to improve the physical and chemical properties of bioliquids through blending and emulsification, or they are generated as a side product during the production of bioliquids.

2.1. Fast pyrolysis bio-oil (FPBO)

When evaluating the technical feasibility of bioliquids used in power generation applications, it is important to first discuss the upstream processes of production and feedstock use in order to link the challenges that occur in end-use with the particular process parameters or feedstock properties. Hence, a condensed overview of this matter is first given for FPBO.

2.1.1. Feedstock and fuel processing

Pyrolysis is a thermochemical process run at atmospheric pressure that converts solid organic materials into a liquid (bio-oil), a solid carbonaceous material (char), and non-condensable gases. Depending on the feedstock type, particle size, and process parameters such as residence time, temperature, and heating rate, the relative amount of products and their composition can significantly change [10]. Typical process conditions exceed temperatures of 600 °C and have relatively short residence times (a few seconds or less). While slow pyrolysis of lignocellulosic material produces mainly char as a derived product [11], the fast pyrolysis route delivers high fractions of FPBO [12] – a desired bioliquid with an appealing set of properties as an energy carrier.

Different reactor technologies for FPBO were continuously developed in the last decades [13] and some configurations have now achieved full commercial scaling. These reactors are either a type of rotating cone reactor (i.e. as developed by BTG Bioloquids BV, Netherlands) [14] or a type of circulating bed reactor (commercialised by Metso, UPM, and Fortum, Finland) [15]. Recently BTG, in cooperation with TechnipFMC [16], signed an agreement to build four fast pyrolysis plants in Finland [17], replicating the industrial scale unit already demonstrated through the Empyro project, each with a biomass capacity of 5 t/h. The typical energy requirement for the production of FPBO accounts for roughly half of the products' low heating value [18]. As expected, the reported break-even selling price highly depends on production plant size. Most calculations provide numbers around 10–19.5 €/GJ, compared to the fuel oil market price of approximately 10 €/GJ. A plant with a higher production capacity will have the advantage of breaking even at a lower selling price relative to the market oil price, thus making it profitable [18]. In terms of GHG emissions for the entire production of these bioliquids (cradle-to-grave), data on pyrolysis oils is available mostly for its final use in heat generation, with overall values in the range of 7–15 gCO_2eq/MJ [19]. The values are highly dependent on feedstock and process conditions, and can increase by 25–50% if feedstock pre-treatment is required [20].

2.1.2. Fuel properties

In contrast to crude oil, FPBO contains a large number of oxygenated components with high polarity, thus making it immiscible with hydrocarbons. FPBO's Low pH index and high Total Acid Number (TAN) are a consequence of the presence of water and organic acids (formic and acetic acid). Water in FPBO is introduced in two manners, 1) with the feedstock (as biomass moisture) and 2) as a result of the process reaction (process water) [21], i.e. generated by dehydration and degradation reactions [22].

FPBO can be a rather unstable product during storage, in particular when low quality feedstock is used. Typically, phase separation occurs if the water content in FPBO is higher than 30–45% in mass [23]. Crude pyrolysis oil also shows poor ignition properties and low volumetric energy density because of its high oxygen content, even though it features a high density (~1100–1200 kgt^{-1}) in comparison to conventional fuels. Several extensive descriptions and analysis methods for FPBO have been published, among which one method published by Oasmaa and Peacocke [24] details many of the relevant properties of these oils. For use in power generation, a reduction in viscosity is possible with ethanol blending or by producing emulsions with diesel fuel. A comparison of the temperature dependence of FPBO viscosity to other bioliquids mentioned in the paper is presented in Fig. 2.

Presently, two sets of FPBO quality for burners are covered by ASTM D 7544 [25] and the corresponding European standards for boiler FPBO grades are being developed under the auspice of CEN in the EU [26].

2.2. Hydrothermal liquefaction (HTL) biocrude

In order to provide key physical and chemical characteristics of HTL biocrude that are related to power generation, an overview of feedstock and fuel processing along with the resulting fuel properties is given next.

2.2.1. Feedstock and fuel processing

Hydrothermal liquefaction (HTL) is a thermochemical conversion process capable of converting low grade feedstock with high moisture content (such as wet biomass) into a high value biocrude with high heating values. Previous studies have shown that HTL can be applied to different types of feedstock; lignocellulosic biomass (hardwood), algae [27], pomace [28], and sludge and manures [29]. Gollakota et al. [30], provided a comprehensive review of the types of feedstock that have been used for HTL processing to obtain biocrude. The HTL process is typically performed at subcritical water conditions with temperatures between 250 and 370 °C, and pressure ranging from 10 to 30 MPa [31].

The HTL process is different from the pyrolysis process (the comparison is shown in Table 1) as it produces a bioliquid in an aqueous medium that involves a series of complex processes such as solvolysis, dehydration, decarboxylation, and hydrogenation, enabling the conversion of biomass into biocrude. The main factors that further influence the HTL yield include reaction temperature, residence time, reaction pressure, algae loading, and the extraction solvent [32]. Solvent extraction using hexane was reported to give better oil quality with a higher heating value and carbon content but at a lower yield. By increasing the HTL reaction time from 10 to 60 min, lower yields of water soluble biocrude and higher yields of water-insoluble biocrude can be obtained [27].

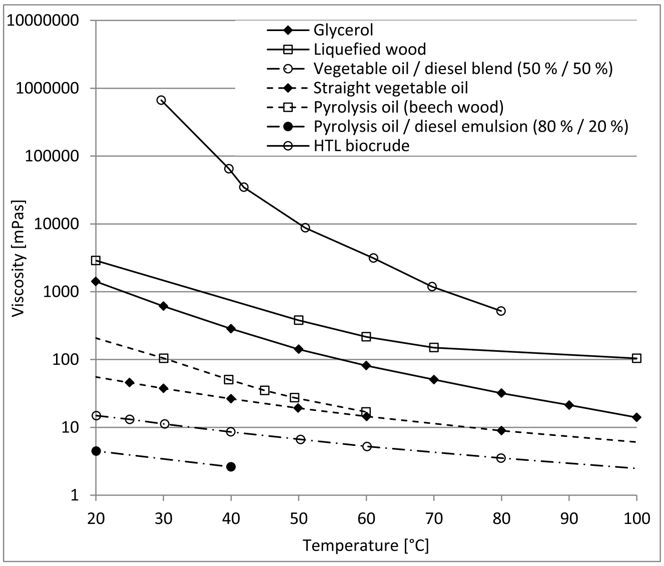

Fig. 2. Viscosity of different bioliquids.

Table 1
Comparison of the biomass thermochemical conversion process of pyrolysis and hydrothermal liquefaction [33].

	Hydrothermal liquefaction	Pyrolysis
Pretreatment	Unnecessary	Drying
Pressure (MPa)	5–20	0.1–0.5
Temperature (°C)	200–400	370–526
Catalyst	optional	No
Heating value	High (~30 MJ/kg)	Low (~17 MJ/kg)
Oxygen content	Low	High
Water content	Low	High
viscosity	High	Low
Fuel upgrade	Easy	Hard

The allocated Global Warming Potential (GWP) of this biocrude production chain (cradle-to-grave) is approximately 9 gCO$_2$eq/MJ, while further upgrading (i.e. to renewable jet fuel) results in ~13 gCO$_2$eq/MJ [34]. The production costs are 13.6 €/GJ in an economically optimised process. Taking into account the upgrading costs, the price of an intermediate HTL biocrude is in a similar range as biomass pyrolysis oils.

2.2.2. Fuel properties

Despite the variation of yield, the calorific values for all the biocrudes were found to be within the range of 32.0–34.7 MJ/kg [29], confirming the universality of the process. Viscosity is approximately 495 mPa at 40 °C [28]. Due to their ability to produce relatively high heating values, biocrudes with flexible feedstock are one of the main advantages of the use of the HTL process. Table 2 compares the properties of biocrudes derived from different feedstock with the pyrolysis oil and biodiesel standard EN 14214. HTL derived biocrudes generally exhibit higher heating values compared to pyrolysis oil, although certain HTL oils could possess a 10-fold higher viscosity. Biocrude can also be upgraded to high quality biofuels via various catalytic processes.

2.3. Liquefied wood

A less widely known bioliquid with an already demonstrated potential for power generation and a low complexity production process is liquefied wood. Condensed information about processing and fuel properties is presented in the following sections.

2.3.1. Feedstock and fuel processing

Liquefied wood is produced from raw wood or other lignocellulosic materials by liquefaction in the presence of polyhydroxy alcohols. The process is essentially a catalytic solvolysis [38]. In contrast to HTL, which requires very high pressures and temperatures to use water as a solvent, catalytic solvolysis is maintained at about 160–200 °C [39–42], at ambient pressure, and in the presence of an acid catalyst [43,44] that accounts for ~1% of the product mass. The process equipment is relatively inexpensive (atmospheric pressures and low temperatures), although the use of corrosion resistant steels is necessary. The process efficiency in terms of mass is 97–98%, 2–3% of the mass balance is filtered in the form of undissolved cellulose fragments (shown in Fig. 3). The estimated energy requirements are approximately 9% of the products' lower heating value (LHV) (i.e. only 2 MJ per kg of produced liquid fraction) [45].

Formulations at 1:1 alcohols to wood ratio produce a stable bioliquid suitable as fuel for power generation [46–48]. Glycerol and diethylene glycol are used as liquefaction agents and p-Toluensulfonic acid (pTSA) as the catalyst. Although the process requires a solvent, its main

Table 2
Comparison of the properties of biocrude derived fuels from different feedstock with pyrolysis oil and standard biodiesel.

Properties	HTL (hardwood) [35]	HTL (algae) [29]	HTL (lignocellulose) [36]	HTL (pomace) [28]	Pyrolysis oil (algae) [37]	European biodiesel standard EN 14214
Flash point (°C)	39	–	–	–	–	>120
Kinematic viscosity at 40 °C (cSt)	11.97	>2.26	>300	495	31.8	3.5–5.0
Pour point (°C)	−12	–	–	–	–	
Total acid number (mg KOH/g)	36.78	11.56–256.5	30–60	108–159		<0.5
Density (kg/m^3)	970.3	970–1040	820–1000	960–990	–	860–900
Heating value (MJ/kg)	40.43	30–43	–	33–38[a]	26.1	>35

[a] Higher heating value.

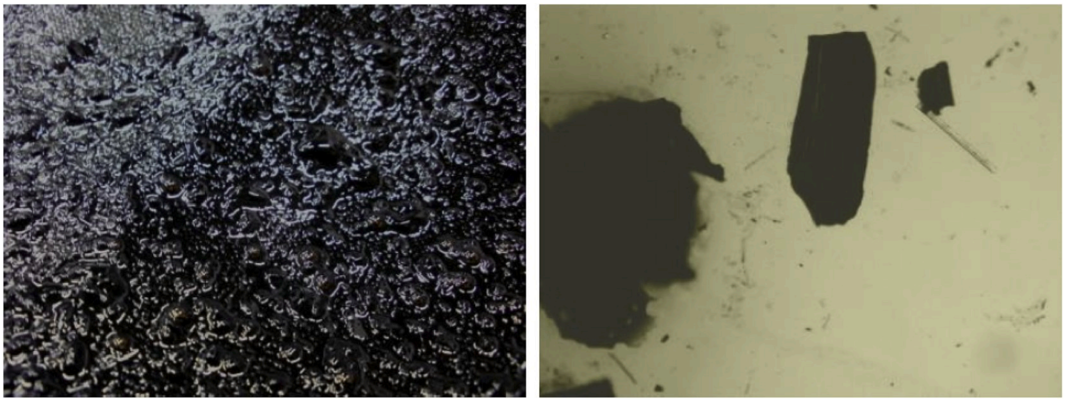

Fig. 3. Left - filtrate of liquefied wood, right - diluted undissolved biomass fragments.

advantage is the potential use of glycerol (as a low-cost substitute for other polyhydroxy alcohols) - a residual product from the trans-esterification of vegetable oils [8,49], which is abundant in the biodiesel industry. The commercial price of liquefied wood is approximately 2.00 €/kg (0.33 €/kWh) when high quality lignocellulosic biomass is used as a feedstock. In the case of low quality biomass and optimised formulation, the price is approximately 1.5 €/kg.

2.3.2. *Fuel properties*

Liquefied wood has a higher viscosity than FPBO (over 300 mm^2/s at 40 °C) and very low moisture content. This is evident from a heating value of above 20 MJ/kg which is higher than that of FPBO. Recently, a formulation using ethylene glycol in substitution of diethylene glycol was produced which succeeded in reducing viscosity [50]. A high temperature dependence of viscosity was also observed. This proved useful, since liquefied wood is chemically stable at temperatures above 100 °C, as well as during storage. However, it is challenging to manipulate this fuel as its viscosity exceeds 1000 mPa at room temperature. Liquefied wood is highly polar and thus immiscible with nonpolar liquids, although it can accept small amounts of water before precipitate starts to form. It mixes well with alcohols, therefore various blends can be made using the latter. With petroleum derived nonpolar fuels it is possible to produce emulsions. Besides high viscosity, the most unfavourable characteristic of Liquefied wood is its pH value (2.5–3.5), although various approaches to elevate its pH to 5.5 have proved successful [47], thus reducing much of the difficulties linked to the durability of materials in contact with such a fuel source. Liquefied wood visually resembles HTL biocrude, although its viscosity is significantly higher [45]. Visual appearance of different bioliquids is presented in Fig. 4. The colour and transparency in Fig. 4 ranges from transparent to dark brown and depends on used feedstock as well as on the underlying process properties. The visual thickness of the flow roughly correlates to viscosity.

2.4. *Straight vegetable oils (SVO)*

Being a highly desired feedstock for biofuel production, SVO can be considered a bioliquid if the conversion to fatty acid methyl esters (FAME) is not the desired utilisation pathway. An overview of the available feedstock as well as key properties that impact its use in power generation application is given next.

2.4.1. *Feedstock and fuel processing*

The simplest form of bioliquids are SVOs which can be extracted from a variety of plants, such as palm, jatropha, rapeseed, sunflower, soybean, nuts, and many others. The extraction of the oil from the seeds or kernels of plants is typically performed by using ram or screw type pressers, which can provide an extraction rate of 65% of oil for ram type

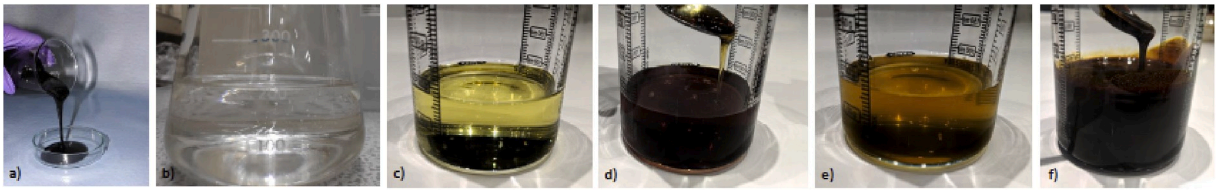

Fig. 4. Visual appearance of (a) Liquefied wood, (b) Glycerol, (c) Used cooking oil, (d) Crude glycerol, (e) SVO (jatropha), (f) HTL Biocrude.

pressers and 95% of oil for screw type pressers [51]. Another method of oil extraction is via chemical extraction with solvents such as n-hexane, bioethanol, or isopropyl alcohol [52]. A biological extraction method from crushed seeds has also been explored by using enzymes such as alkaline protease. The main disadvantages of the chemical and biological extraction methods are the production of hazardous waste water and long processing times [51].

2.4.2. Fuel properties

The benefits of SVO as a bioliquid are mainly attributed to its biodegradability, renewability, and low sulphur content. However, the viscosity of SVO is about an order of magnitude higher than that of diesel, as presented in Table 3, but still lower than FPBO, HTL biocrude, or liquefied wood. Blending and preheating SVO with conventional diesel or biodiesel is one way to overcome the issue of high viscosity [53]. Yilmaz and Morton [54] demonstrated that SVO viscosity was reduced by a factor of 6 when preheated to 90 °C compared to its viscosity at room temperature, making this approach an attractive substitute for blendingwith diesel. SVO has a higher heating value than pyrolysis oil due to its low oxygen content, making it a potential candidate for stationary combustion systems. Similar to other bioliquids, further processing can be done to upgrade the oil quality, reduce its viscosity, and increase its heating value. The most widespread upgrading process is the conversion to biodiesel via the process of transesterification. The most important properties of different SVOs are presented in Table 3.

Table 3
Properties of selected SVOs. Data obtained from Ref. [55].

Fuel	Calorific Value (kJ/kg)	Density (kg/m^3)	Viscosity at 27 °C (mm^2/s)	Cetane number
Diesel (benchmark)	43.350	815	4.3	47.0
Sunflower oil	39.525	918	58.5	37.1
Cotton seed oil	39.648	912	50.1	48.1
Soybean oil	39.623	914	65.4	38.0
Corn oil	37.825	915	46.3	37.6
Opium poppy oil	38.920	921	56.1	–
Rapeseed oil	37.620	914	39.2	37.6

2.5. Bio-alcohols and biodiesel

Although not always considered a bioliquid, bio-alcohols and biodiesel are often used for blending purposes to reduce the viscosity, increase the heating value, and improve other properties of the above listed bioliquids. The following sections comprise a brief overview of key properties and utilisation techniques of bioliquids.

2.5.1. Feedstock and fuel processing

Bioethanol, although not considered a bioliquid, is produced from fermentation processes, often through feedstocks that contain sugar, starch, or cellulose [56]. Sugar based biomass feedstock can be directly converted into bioethanol via fermentation or produced from either gasification-synthesis, gasification–fermentation, or hydrolysis–fermentation [57,58]. Cellulosic feedstock such as wood, straw, and bagasse require additional processes such as hydrolysis or saccharification to breakdown the cellulose complex molecule into simple sugars prior to fermentation [59,60]. Bioethanol is currently utilised as a substitute fuel for gasoline, commonly used in countries such as Brazil, the US, as well as the EU [61]. The ethanol standard specification developed by Europe and the US are EN 15376 and ASTM D-4806, respectively. Its relation to bioliquids is that it is often used as a blending agent for FPBO, HTL biocrude, or liquefied wood.

Biodiesel, produced with a transesterification process from fatty acids, is currently a fully standardised fuel, conforming to the European Union (EU) and US standards, i.e. EN14214 and ASTM D-6751, respectively. It has proven to be a viable substitute fuel to be blended with diesel for use in compression ignition engines [62]. At present, biodiesel is widely used for transport in Europe, the US and Southeast Asia via the blending of 2–10% with conventional diesel [63,64]. In terms of bioliquids, it is an important blending agent often used with SVO to reduce its viscosity and to keep the content of renewable feedstock high.

Glycerol can be recognized as an important side product of transesterification process during biodiesel production. It can also be considered a low cost bioliquid with a market price of 0.011 €/MJ [65]. Although it is most often upgraded to a purity of over 99.5% for use in pharmaceutical and food industry (this increases the market price to 0.079 €/MJ), large stocks and a low market uptake also make it a viable option for power generation if purification is performed only to a moderate extent.

2.5.2. Fuel properties

Being an alcohol, ethanol is considered a light fuel, which can be blended in low volumes with gasoline (less than 10%) for use in engines as biofuel, or can be used directly as a fuel, without prior blending. In this case it typically contains about 8% of water. Its good solubility is mainly a consequence of the nonpolar carbon chain and polar hydroxyl group, thus the solubility of any alcohol in other nonpolar or polar liquids depends on the ratio and strength between carbon chains and the hydroxyl group [66]. Since alcohols have a high polarity, they are considered good solvents for pyrolysis oils [67,68] with the ability to reduce the oils' initial viscosity [69]. On the other hand, ethanol is not completely soluble in liquefied wood, thus different solvents (i.e. di-chloromethane) are required for the complete dissolution of such a blend [50].

The properties of biodiesel share similarities to those of diesel fuel which enables its drop-in use. The most recognized differences are its oxygen content that reduces the LHV by up to 8% in comparison to diesel [70], and its high flash point which limits its performance at low temperatures. It is also prone to microbial degradation which results in a short shelf life. Hence, for transport applications the EN590 standard limits the biodiesel content to 7% in order to overcome these challenges.

Residual glycerol from biodiesel production is a bioliquid with high viscosity and high oxygen content and is usually heavily contaminated with catalyst residuals and mineral matter. High sodium content is a consequence of sodium methylate ($NaOCH_3$) or sodium hydroxides ($NaOH$) used as a catalyst, while Ca, K, Mg, and P are a consequence of feedstock carryover linked to various parameters such as soil conditions and process contamination from external substances. Apart from inorganic contaminants, crude glycerol also contains substantial amounts of methanol (in excess of 20%) and water (1–3%) [71]. As a bioliquid, a notable property is its very high oxygen content (52%) and high viscosity, with values close to liquefied wood and FPBO. If purified, methanol and water are removed together with inorganic components, usually resulting in a purity of over 99.5%. A comparison of the properties of bio-alcohols and biodiesel, together with their solubility in bioliquids, is presented in Table 4. Data for ethanol is taken from Ref. [67,72], for glycerol from [73], crude glycerol from Ref. [74], and biodiesel from [70]. Solubility data for FPBO is adopted from Ref. [66,75].

2.6. Overview of properties of bioliquids

As discussed and presented in the previous sections, properties of bioliquids vary depending on the feedstocks used, as well as on the process parameters. To provide typical values for variations of bioliquids that are targeted for combustion applications, the original research data from this field is presented in Table 5 for a wide range of bioliquids that will be discussed from a power generation aspect. Hence, the main properties that are most relevant for combustion applications are

Table 4
Properties of bio-alcohols and biodiesel.

Fuel	Ethanol	Glycerol (crude)	Glycerol (99.5%)	Biodiesel (Canola oil)
Density (kgdm^{-3})	0.817	~1.22	1.26	0.878
Heating value (MJ/kg)	22.8	13.5	16.0	38.75
Water content (wt. %)	–	11.85	–	–
Viscosity at 40 °C (mm^2 s^{-1})	1.1		230	5.0
Solubility in FPBO (%)	>95	n.a.	<5	<10
Solubility in liquefied wood (%)	<10	n.a.	>90	<5

presented in order to provide a basis for the efficient identification of the challenges linked to power generation with bioliquids presented in the next section.

3. Power generation with bioliquids

When discussing power generation with bioliquids, the above processes, as shown in Table 5, offer products with a relatively high variability of physical and chemical characteristics that are inherently linked to specific feedstocks and production processes. Since the carry-over of different contaminants is in most cases highly complex, and the multicomponent composition prevents the use of advanced power generation technologies (i.e. fuel cells, hybrid systems), the main pathways for the utilisation of bioliquids comprise conventional thermal systems with internal and external combustion. These include:

- reciprocating engines with internal combustion (often denoted as Internal Combustion Engines - ICEs),
- turbine engines (often denoted as Gas Turbines – GTs) and
- atmospheric combustion devices.

As the availability of bioliquids is highly dispersed with current capacities being relatively low and significant efforts being oriented towards efficient distributed power generation using locally available resources, this review is principally targeting systems for distributed power generation that offer flexibility to the grid and are ideally used for onsite power generation. In this light, large GTs are omitted, as they most often exceed power outputs of 10 MW and hence require an abundant fuel source and extensive fuel supply logistics which reduces their flexibility when taking into account the wide and highly dispersed portfolio of available bioliquids. The use of bioliquids in atmospheric combustion devices can be considered as a feasible first step towards their wide-scale utilisation. However, current and future guidelines on energy efficiency suggest that this approach is less future-proof, as it features low effective efficiency unless it is used solely for heating applications. Both aspects can be well addressed by introducing combined heat and power (CHP) systems that enable the conversion of bioliquids to power and heat simultaneously with high efficiency. Based on these observations, the main focus of this work is on ICEs with low power output, and micro gas turbines (MGT) that can reliably support the majority of distributed CHP units, hence providing the most relevant guidelines for the next decade.

3.1. *Key limitations*

ICEs generally require fuels with very low viscosity, high volatility, very low evaporation residue (preferably with low ash content), and sufficient corrosion performance. While spark ignition ICEs are majorly limited by the fuel's volatility and generally require a low presence of evaporation residues, compression ignition engines are capable of firing a broader set of fuels since they rely on spray combustion, thus making it possible to utilise fuels that contain small amounts of evaporation residue. As the process of mixture preparation in these ICEs happens in a shorter timeframe and in most cases fully within the combustion chamber, the limiting properties in such systems are usually viscosity, surface tension, and the evaporation curve of the fuel. These parameters limit the atomisation ability and thus the mixture formation for a high-quality combustible blend. Simultaneously, some similarities of compression ignition engines can be drawn with MGTs, where viscosity and surface tension are also the major limiting factors. However, MGTs tend to have higher fuel flexibility as they employ a continuous combustion process and significantly longer residence times for the combustible mixture and they thus enable the use of fuels with lower evaporation rates. Although this advantage is currently not widely exploited in commercial MGTs, the potential is fully proven by existing research results [73].

Table 5
A comparison of the physical and chemical properties of bioliquids.

Properties	Unit	Fast Pyrolysis Bio-Oil [67,76]	HTL Bio-Crude [31,77]	Liquefied Wood [43,48,50]	Vegetable Oil [52,78–80]	Used Cooking Oil [80]	Ethanol [67,72]	Crude glycerol [74]	Glycerol (99.5%) [73]	Diesel [81]
C	wt. % db.	54.97	83.0	47.6	76.5	76.3	44.93	–	42.19	34.48
H	wt. % db.	6.43	6.7	7.98	11.3	11.7	12.30	–	9.14	65.51
N	wt. % db.	0	0.2	0.19	0.33	0.02	0.02	0.023	0	0
S	wt. % db.	0.013	0	0.89	0	0	0	–	0	0
O	wt. % db.	38.56	10.0	43.34	11.87	11.98	42.7	–	48.67	0
pH	–	2.7	–	2.5–3.5	–	–	7	–	–	–
Ash content	wt. % db.	0.02	0.07	0	0.001	0.01	0	1.13	0	–
Water content	wt. %	22.5	16.9	<2	0.13	0.08	7.2*	11.85	–	–
Kinematic viscosity at 40 °C	mm^2 s^{-1}	37.01	>11.97	>300	27.8–40	38.15	1.1	–	230	2.7
Density at 25 °C	kgdm^{-3}	1.192	>0.970	1.3	0.922	0.911	0.817	~1.22	1.26	0.85
Stoichiometric Ratio	–	5.3:	–	6.8	–	–	9.8	~4.5	5.19	9.76
LHV	MJkg^{-1}	17.32	35.9–40.43	23.93	36.2–39.7	36.43	22.76	~13.5	16	43

3.2. Evaluation of bioliquids for power generation

When bioliquids are considered as new fuels for the aforementioned combustion systems, a comprehensive evaluation of their suitability is usually necessary. Coupled analyses addressing fuel properties, combustion, and emission formation phenomena, as well as the degradation of materials, and the degradation of component functionality have been proposed [82], Fig. 5. Such a holistic approach ensures that the design space is constrained early in the design or adaptation process, providing a basis for efficient and highly targeted adaptation procedures.

3.3. Reciprocating engines

ICEs, either of the spark or compression ignition type, are devices that have moderately benefited from the use of bioliquids. Currently available work goes from fundamental chemical analyses and lab scale testing to a limited variety of commercial and industrial proof of concept operations.

3.3.1. Bioliquids with properties close to conventional fuels

Straight vegetable oils have been assessed for replacing diesel in internal combustion engines over the years. It is clear from the previous sections that, although SVOs are among bioliquids the ones with properties most similar to diesel fuel, careful consideration still needs to be taken due to their discrepancies, which can directly impact the performance of the combustion system employed for their use. Several authors have studied fuel blends with soybean [83–85], sunflower oil [86,87], cashew nut shell oil [88], honge, neem and rice oil [89], jatropha curcus [90], ternary blends of soybean, sunflower, canola, corn, olive and hazelnut oils [91], papaya and watermelon seed oil [92], etc. All blends showed great variance in engine performance and emissions, with some denoting a reduction in CO and HC emissions, whilst others reported opposite trends, with great variance in NO_x emission profiles across the literature.

3.3.1.1. Fuel property specific challenges. In most analysed feedstock, an increased viscosity required engine adaptations in order to improve combustion profiles. Ramadhas et al. [55] summarised the advantages of SVO use as a reduction in import cost, development of new industries and suppliers, the use of biodegradable raw materials obtained mainly from renewable sources with low aromatic and sulphur contents, whilst having adequate heating values, and properties that enable the use of SVO in current engines with minor retrofitting. However, these advantages need to be considered in light of problems such as variability in feedstock, difficulty during storage, unreliable flashpoints, difficult operation during cold weather, necessary improvements in fuel delivery system, and the overall uncertainty in the continuous availability of these bioliquids.

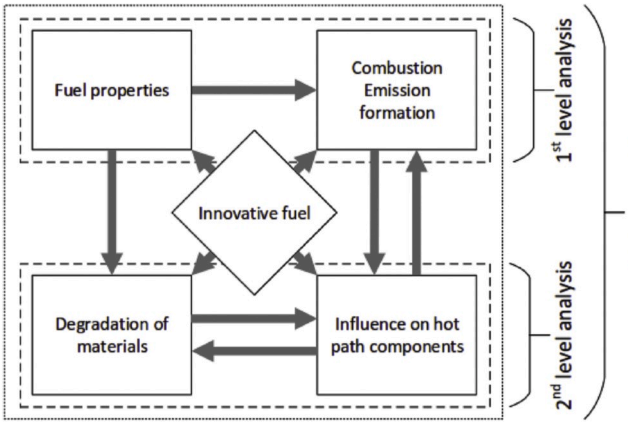

Fig. 5. Proposed approach for the feasibility analysis of innovative fuels [82].

3.3.1.2. Engine adaptations and durability. As pointed out by Agrawal et al. [93], the most vulnerable parts of an internal combustion engine when using these bioliquids are the piston, the cylinder, the piston ring, the bearings, the crankshaft valves, the camshaft, and the lubricating pumps. From the studies of Shina and Agrawal [94], the results denote carbon deposits on various engine components due to the thermal and oxidative degradation of the lubricating oil, as well as incomplete combustion, which bioliquids are prone to. These deposits decrease performance and efficiency whilst increasing maintenance, potentially leading to engine failure. While difficulties linked to the degradation of the lubricating oil can be addressed by adjusting the oil additives, a dilution of the oil with unburnt liquid SVO can only be tackled with a high enough fuel evaporation rate. Despite the challenges, the overall durability of CHP units that use SVO fired ICEs was already achieved and several suppliers now offer CHP units using SVO as a fuel (8–340 kW units are widely available). It is worth noting that no significant improvements of injection systems have been reported and most of the studies rely on the original installed single fluid pressure injection nozzles.

3.3.1.3. Engine performance and emissions. Most studies that analysed SVO showed that both brake and torque were reduced when these bio-oils were employed. For example, rapeseed oil has been used in combination with other additives (i.e. diesel, n-butanol, cooking oil, etc.) [95,96] which resulted in a decrease in torque, brake power, and exhaust gas temperature with an increase in specific fuel consumption. A clear reduction in carbon based emissions (i.e. CO and HC) has also been reported. Hemmerstein et al. [97] evaluated the use of filtered rapeseed oil, which in Germany was considered a major agricultural raw material with fuelling potential. Experiments denoted lower mechanical stress and lower combustion noise, with higher CO and HC emissions but lower NO_x and Particle Matter concentrations. Similarly, other authors have studied fuel blends with various feedstocks [83–85] showing great variance in performance and emissions, with some works denoting a reduction in CO and HC emissions, whilst others reported opposite trends, with great variance in NO_x emission profiles across the literature.

Other experiments denoted lower mechanical stress and lower combustion noise, with higher CO and HC emissions but lower NO_x and particle mass emissions. Unfortunately, the trend is not consistent with other studies [95,97] which showed a reduction of emissions when SVOs were mixed with fossil based additives and other bioliquids. Therefore, it can be concluded that emissions and performance are highly dependent on the employed system and the conditions of interest.

3.3.2. Highly viscous bioliquids

Pyrolysis oils, as previously depicted, have a role to play in the implementation of novel bioliquids for fuelling purposes. Although the literature is not extensive, studies present this option as a viable, clean alternative to current fossil fuels for backup power generation or for continuous onsite operation. The use of FPBO/EtOH blends has been evaluated for combined heat and power (CHP) applications employing modified engines [69], denoting the higher volumetric fuel consumption but similar electrical efficiencies to conventional systems [69]. Similarly, Dai et al. [98] performed studies to demonstrate the use of Camellia oleifera (COS) shell and stillingia oil (SO) for the pyrolysis of bioliquids and their potential use in ICEs, confirming the potential use of the former. Other potential bioliquids obtained from pyrolysis that were assessed for their application in ICE include fast growing brown salwood (Acacia mangium Willd) residues [99], jatropha [100], microalgae (Chlorella sp.) [101], wood [102], cardoon (Cynara carinculus L.) [103], lignocellulosic biomass [15], etc.

3.3.2.1. Fuel property specific challenges. In terms for FPBO, proper atomisation of the fuel is of utmost importance as its surface tensions and viscosities are different to those of fossil blends for which ICEs are usually designed, thus requiring other additives (i.e. ethanol) to improve atomisation properties [69]. Stamatov et al. [104] recognized the poor atomisation and lower calorific value. It was observed that there must be a balance between the fuel and possible polar additives to avoid a further reduction of heat flux from these flames [104]. Moreover, the high moisture content reduces flame temperature and the heating value whilst increasing the ignition delay [105]. Unstable thermal output and storage difficulties due to the oxygenated functional groups accompanied by polymerisation and deterioration at temperatures above 100 °C [15] present an obstacle for further implementation. Corrosion can also occur as a consequence of the low pH values attributed to the presence of organic acid compounds. Pyrolysis oils also contain traces of ash (with sodium, potassium, vanadium, and calcium traces) that tend to produce high corrosion and deposition at high temperatures [15]. Char in these bio-oils can also cause blockages, reduce combustion performance, cause cracking of the bio-oil, present higher viscosities, etc.

3.3.2.2. Engine adaptations and durability. As previously depicted, the use of bioliquids presents various challenges that can be tackled by employing engine adaptations, especially for materials and atomisation systems. Bridgwater [106] concluded that, for FPBO, mild steel was not suitable for handling or storing such bioliquids, and suggested polypropylene piping to overcome the problem. This could also be applicable to various parts of the engine fuel delivery system. An extensive review study on FPBO use for power generation [107] suggests that the originally used injection nozzle materials and seals are not suitable for use with FPBO and that the contamination of the lubricating oil is possible.

3.3.2.3. Engine performance and emissions. When FPBO were used, the results depicted the effect of these bio-oils in the combustion process with higher cylinder pressures and lower emissions at medium bio-oil concentrations in blends, after which the lower heating value and higher densities can lead to a decline in the thermal performance of the overall system [100]. On the contrary, a modified 48 kW diesel engine enabled the use of FPBO, showing higher volumetric fuel consumption but similar electrical efficiencies [69].

3.4. *Micro gas turbines*

While ICEs present high flexibility and availability, with prices and technological maturity superior to GTs, in terms of bioliquids GTs feature a particular advantage for the utilisation of fuels with challenging physical and chemical properties – continuous combustion, which they rely on. This characteristic should, at least after preliminary observations, enable the utilisation of fuels that exhibit less favourable physical and chemical properties, as long as they feature sufficient homogeneity. Similar to ICEs, GT design is mostly built around fossil-derived fuels [108] with specific tailoring for different applications [109], and fossil fuel types [110]. The most demanding sector is aviation, where the miscibility of fuels from alternative sources with conventional fuels is strictly imposed [111], and only fully compatible fuels can be used in order to avoid the specific tailoring of existing engine units and infrastructure [112]. However, in stationary power generation applications, the flexibility of technology is much higher. Hence, specific adaptations can be implemented to accommodate the challenging physical and chemical properties of alternative fuels, where the main guideline is preserving the GT thermal power, which can be met by adjusting the fuel mass flow. Such an approach opens up a significant opportunity to obtain the superior fuel flexibility of GTs and possibly allow the utilisation of a large portfolio of bioliquids.

In relation to GTs, bioliquids were previously investigated in different setups that can, according to their technical complexity, be grouped into the following categories:

- Commercial setups with modern design, presenting the best available technology at the time of the performed research with little to no fuel-specific modifications,
- Auxiliary power units (APUs) and small propulsion engines, adapted for the use of specific fuels,
- Small standalone purposely built test rigs which mimic the conditions present in commercial setups.
- Dedicated test rigs for isolated components.

Bioliquids in large GTs are almost exclusively investigated in either commercial setups or dedicated test rigs for isolated components, since extensive adaptations are expensive, require significant downtime, and the process of their development features long turnover times. Hence, the research in this area is limited. On the other hand, the availability and affordability of micro GTs (MGTs), with comparable power outputs to ICEs, and also the possibility of reproducing the conditions in small standalone test rigs and APUs leads to widespread efforts to investigate the combustion of bioliquids in MGTs.

Across the literature, no specific guidelines for categorizing MGTs are available. However, based on extensive research and review, they are most often defined by intervals of power output in MGT setups that are available on the market. As previously reported [129], these range from 15 kW to 1 MW ((30–400 kW [113], 30–330 kW [114], 25–500 kW [115], 15–300 kW [116], 30–100 kW [117], 10–200 kW [117], <1 MW [118], <300 kW [119]). Along with these constraints, it is worth mentioning that all MGTs, defined with an upper limit to their power outputs, feature a single stage compressor with no active blade cooling technology. Hence the pressure ratios are usually below 4 bar and peak temperatures are lower than 1000 °C. To obtain a high effective efficiency with such specifications, modern MGT setups additionally rely on exhaust gas heat regeneration. Furthermore, to keep the total cost of ownership low, MGTs are often available in serial production (which lowers the production costs in terms of € per kW) and units are usually not tailored for specific installation sites.

3.4.1. *Bioliquids with properties close to conventional fuels*

SVO presents the most natural pathway for the utilisation in MGTs because of its similarities with conventional fuels. As its viscosity, density, and heating values roughly mimic the values of conventional fuels, SVO utilisation is possible without significant adaptations to the MGT setups. Thus, vegetable oils, their blends with Fatty Acid Methyl Esters (FAME), and diesel have been tested [120] with positive results. Soybean oil [35] and SVO from several other feedstocks (rapeseed, sunflower, and soybean) [121,122] have also been employed in MGTs, demonstrating the feasibility of their implementation as fuel sources. More demanding fatty acids included an experimental evaluation of waste trap grease [123], and treated waste cooking oil [124], showing the potential of these low grade energy sources.

3.4.1.1. Fuel property specific challenges. In most cases, the challenges of fuel delivery and power output that occur with fatty acids or waste fats in MGTs are linked to their density and LHV which alter the volumetric energy density of the fuel [120,123], thus requiring a revised sizing of fuel system components. In the case of waste fats and SVOs, their viscosity is generally at least an order of magnitude higher than those of fossil fuels. This is shown in Table 5 and Fig. 2. For Fig. 2, data is obtained from several sources: vegetable oil and its blends [35], HTL biocrude [36], liquefied wood [45], glycerol [73], pyrolysis oil and emulsions [125]). Higher viscosity poses a significant challenge for atomisation [78,126] and the accompanied pressure losses in the fuel system. These are often tackled by preheating the fuel to exploit the temperature dependence of viscosity. This preheating leads to molecular composition and acidity becoming important. In vegetable oils, a ratio between linoleic and oleic acids, for example, plays an important role in the thermal stability of SVO, and consequently at the formation of deposits under elevated temperatures [120], whereas acidity is the main factor influencing the corrosion of fuel system components. Furthermore, the miscibility with different solvents (usually ethanol, methanol, diesel, or biodiesel) enables a reduction of viscosity with blending [35].

Other important parameters are impurities and fuel degradation at high temperatures. Although the fuels are in most cases filtered to at least 5 μm nominal, the possible re-condensation of components and the formation of thermal degradation products during preheating often causes valve and nozzle clogging during extended use. Specific molecular composition also influences the evaporation curve of SVO from different feedstocks and generally prolongs the droplet residence time due to the high boiling points of the contained components [127]. Altered combustion kinetics simultaneously affect the flame shape, temperature, and flow field in the combustion chamber. Finally the molecular composition, combined with the possible content of inorganic contaminants is important in terms of hot corrosion and the formation of deposits– either on hot path components, fuel injection nozzles, or pre-vaporising surfaces in MGTs [78].

3.4.1.2. Engine adaptations and durability. Although the challenges linked to the utilisation of SVO and waste fats in MGTs are significant, currently most available studies rely on integrated injection nozzles that are originally delivered with MGT setups [122,128]. However, the fuel system changes needed for the use of SVO comprise additional adequately sized pumps and valves (in accordance with SVO volumetric energy density). This is often done by designing a parallel feed system [123,128] and dedicated filtering with single or two-stage preheating. Two-stage preheating is selected to elevate the viscosity before the primary pump, and then again before the booster pump, which brings the viscosity close to the desired level. Otherwise, currently accepted limits for viscosity in commercial setups are 15 mm^2/s [108], 12 mm^2/s [72], and 10 mm^2/s [129].

When using SVO or blends with diesel content of up to 25%, available studies do not report adaptations to the combustion chambers, although they rely on a modified startup and shutdown sequence [35, 123,128]. Since measurements are mostly performed in short time intervals (a few hours of operation in one run), no advanced self-adjusting control algorithms are implemented. All major studies in this area report difficulties after a few hours of operation with deposit formation on the injection nozzles. The problem is caused by the following phenomena:

- Insufficient atomisation, slow evaporation rates, and droplet impingement on the mixing tubes (Fig. 6-left) that occur in systems which employ pre-vaporising tubes. Any evaporation residue, either in the form of organic particle matter or ash causes a build-up of deposits and negatively affects the flow phenomena, hot corrosion resistance, and thermal loading. After prolonged operation the deposits mostly contain P, Fe, Na, Cr, Ni, and other elements in trace amounts [78].
- Low thermal stability of the fuel due to the presence of double bonds (reflected in the iodine number of the SVO). Fig. 6-right, shows a consequence of thermal degradation of the fuel on the nozzle's external surfaces. This is mainly caused by exposure of the nozzle to high temperature environments in the primary zone of the combustion chamber. The severity of the phenomena partly relies on the preheating process of the fuel since the fuel acts as a cooling medium for the nozzle.

3.4.1.3. Engine performance and emissions. With bioliquids, studies often report a reduced stability of engine operation through pressure ratio fluctuations or exhaust gas temperature variations that are larger than those of fossil fuel sources [35]. Efficiency and power are in most cases maintained to similar levels as with the original fuels [35,128, 130].

Emissions wise, great variations in particle number, particle mass [130], and NO_x [123] are reported. As opposed to ICEs, CO and THC emissions in most MGT cases are reduced when increasing power while using SVO [128]. Since the MGTs power output is a function of excess air ratio in the primary zone of the combustion chamber, higher power outputs increase the temperature levels inside the combustion chamber, thus aiding in the reduction of incomplete combustion products. The effect is clearly visible in Fig. 9 and Fig. 10, where different combinations of bioliquids and MGTs are evaluated versus power output, since larger MGTs often rely to higher turbine inlet temperatures.

3.4.2. Highly viscous bioliquids

Highly viscous bioliquids usually require extensive adaptations of different components. A handful of studies researched the combustion of FPBO blended with either JP4 aviation fuel or with diesel fuel [125,131, 132]. More challenging slurries of char and JP4 were tested as well [131]. Blends of FPBO and ethanol were also investigated in a small scale (30 kW) combustor [132] and aircraft derived APU [67]. An extensive analysis was performed with liquefied wood derived from forest residues, which was first proposed as a fuel in the 90s [133]. Several formulations were tested, according to their suitability and biomass content, all without blending with low viscosity biofuels [45–47,134]. A continuation of such an approach followed through on the use of glycerol [73] and mixtures of glycerol/diethylene glycol

Fig. 6. Deposits on vaporisation tube after utilisation of SVO [78] (left), deposits on injection nozzle after utilisation of waste grease (right).

[134]. Recently, a study with liquefied wood/ethanol blends was published [50], denoting the possibility of using a relatively simple MGT setup. As per HTL biocrude, although it is a promising bioliquid, the authors do not know of any directly fired MGT test yet. However, current technical advances are opening a way to investigate non upgraded HTL in the near future. The available research on MGTs utilisation is briefly recapped in Table 6.

3.4.2.1. Fuel property specific challenges. Out of the many fuel properties that affect the fuel system design, the most significant are those linked to fuel handling challenges, which notably impact the sizing of separate components and subsystems. The most recognized are heating value, viscosity, density, molecular composition, as well as pH values. A major challenge for bioliquids is also their highly complex molecular composition with high oxygen content, and their instability at elevated temperatures and during storage. Although high oxygen content is perceived as a challenge, it has been shown that it can significantly improve the particle mass and NO_x emissions, bringing them to orders of magnitude below those of conventional fuels [135]. Other challenges include possible ash content, water content, phase separation with FPBO, and the inclusion of solid particles which are difficult to filter or that start to form during the fuel conditioning process.

3.4.2.2. Engine adaptations and durability. The required approaches to tackle the above-mentioned challenges are roughly similar to those of SVO. However, a wide spectra of bioliquid compositions require a comprehensive evaluation of the impact, that the listed fuel properties and their relations have, during the development phase of a MGT. Thorough guidelines on proper adaptation of key components have been reported for the below listed components [126,136].

3.4.2.2.1. Fuel system. When addressing fuel system components, the selection of correct materials is crucial. It affects the durability of the fuel systems, mitigates the corrosion of the components as well as the downstream migration of contaminants that at the same time also impact the hot-path deposit formation. The selection of materials can be supported with relatively inexpensive immersion tests of the used materials in the target bioliquid. For detailed analysis, dedicated corrosion evaluation is usually employed [46]. Failure to select the appropriate materials can lead to dissolved corrosion products in the fuel which then negatively affect the hot components [46]. In such cases, the composition of hot deposits might reveal large contents of contaminants (Fe, Ni, Cr) which are usually not present in bioliquids.

The thermal degradation properties of bioliquids, which are often highly oxygenated, present an important design parameter. Due to often reported low chemical stability, the preheating that is required to exploit the temperature dependence of viscosity has to rely on low temperature heating elements in order to reduce the exposure time of bioliquids to high temperatures [45,50,123]. Two approaches are possible, either low temperature heaters that allow a relatively low flow velocity of the heated bioliquid or high temperature heaters that require a high flow velocity in order to minimise the boundary layer thickness, where temperatures are the highest. The latter approach is less suitable, as it generates substantial pressure drops due to the high viscosity of the treated bioliquids.

3.4.2.2.2. Injection system. A wide range of injection nozzles can support the appropriate spray formation of bioliquids. In most cases, the original equipment manufacturer (OEM) nozzles were used in MGTs. As they are suited to conventional fuels, the blending of bioliquids with lighter fuels was employed to meet the nozzle's requirements for surface tension and viscosity. However, the application of simple pressure atomisation was demonstrated to be disadvantageous, since fuel mass flow significantly impacts the spray formation dynamics [137]. To circumvent this challenge, air-blast and air-assist nozzles were introduced that exhibit little sensitivity to different fuel mass flow rates and feature a comparable droplet size distribution across the operation

Table 6

Studies addressing bioliquids in MGTs, partially adopted from Ref. [129].

Title	Year	Turbine engine	Fuel type	Ref
Exhaust emissions from liquid fuel micro gas turbine fed with diesel oil, biodiesel and vegetable oil	2013	Garrett GTP 30-67	Diesel no. 2, Biodiesel, Vegetable oil, Biodiesel/ Vegetable Oil Blend.	[120]
Evaluating high volume blends of vegetable oil in micro-gas turbine engines	2017	Model jet engine, Sr-30	ULSD Diesel, Vegetable Oil (soybean).	[35]
The impact of spray quality on the combustion of a viscous biofuel in a micro gas turbine	2014	DG4M-1	Diesel no. 2, Vegetable Oil	[121]
Straight vegetable oil use in Micro-Gas Turbines: Experimental analysis		Capstone-C30	Diesel fuel, Straight vegetable oil and their blends.	[127]
Straight vegetable oil use in Micro-Gas Turbines: System adaptation and testing	2012	Capstone C30	Diesel fuel, Straight vegetable oil and their blends.	[78]
Combustion of waste trap grease oil in gas turbine generator	2010	Allison gas turbine - D424A	Diesel, Waste trap grease oil.	[123]
Experimental analysis of a micro gas turbine fuelled with vegetable oils from energy crops	2014	Solar T-62T-32	Straight vegetable oil: Rapeseed, Sunflower, Soybean in various blends with diesel.	[122]
Biodiesel Airblast Atomisation Optimisation for Reducing Pollutant Emission in Small Scale Gas Turbine Engines	2007	Capstone C30	Diesel fuel, Biodiesel (from soybean production), Pure ethanol (E100).	[140]
Performance and emission characteristics of biofuel in a small-scale gas turbine engine	2010	30 kW gas turbine engine	Soy and canola biodiesel, recycled rapeseed biofuel and their 50% blends with Jet-A fuel, 50% blend with hog fat biofuel.	[141]
Spray atomisation of bio-oil/ethanol blends with externally mixed nozzles	2016	Twin fluid externally mixed nozzles	Bio-oil, Bio-oil blends with ethanol (20:80, 40:60 = Bio-oil: EtOH), ethanol and diesel.	[142]
Pyrolysis oil utilisation in 50 kWe gas turbine	2015	DG4M-1	Pyrolysis oil-diesel fuel mixtures, and diesel as reference fuel.	[125]
Alternative feedstock for the biodiesel and energy production: The OVEST project	2013	Capstone C30	Treated waste cooking oil.	[124]
Hydroprocessed Renewable Jet Fuel Evaluation, Performance, and Emissions in a T63 Turbine Engine	2012	T63-A-700 Allison	Hydroprocessed renewable jet (HRJ) fuel and blends 50%/ 50% with JP-8, 16% bio-aromatic/ tallow-HRJ blend.	[143]
Quantification of aldehydes emissions from alternative and renewable aviation	2014	Artouste MK113 APU	Jet-A1, two HEFA, FAE (Fatty Acids Ethyl Ester), GTL (Gas to Liquid).	[144]

(*continued on next page*)

Table 6 (*continued*)

Title	Year	Turbine engine	Fuel type	Ref
fuels using a gas turbine engine				
Wood, liquefied in polyhydroxy alcohols as a fuel for gas turbines	2012	Experimental MGT	Liquefied wood, Diesel fuel	[43]
Microturbine combustion and emission characterisation of waste polymer-derived fuels	2014	Experimental MGT	Liquefied wood, Tire pyrolysis oil, Mixture of glycols, Diesel fuel	[134]
Advanced fuels for gas turbines: Fuel system corrosion, hot path deposit formation and emissions	2016	Experimental MGT	Liquefied wood, Tire pyrolysis oil	[46]
Use of Pyrolysis-Derived Fuel in a Gas Turbine Engine	1983	J69-T-29	Pyrolysis oil, Char/JP-4 slurries	[131]
Preliminary test on combustion of wood derived fast pyrolysis oil in a gas turbine combustor	2000		Wood (eucalyptus) Derived fast pyrolysis oil mixed with ethanol, JP-4.	[132]
Emission reduction through highly oxygenated viscous biofuels: Use of glycerol in a micro gas turbine	2019	Experimental MGT	Technical grade glycerol, Diesel fuel	[73]
Performance and emissions of liquefied wood as fuel for a small scale gas turbine	2018	Garret GTP 30-67	Biomass pyrolysis oil/Ethanol blends	[50]
Combustion of fast pyrolysis bio-oil and blends in a micro gas turbine	2018	Garret GTP 30-67	Liquefied wood/Ethanol blends	[67]

range. Additionally, as momentum for the spray break-up is delivered through high velocity air, the flow cross section for the liquid phase is generally larger which enables low fuel delivery pressures while at the same time being suited for high viscosities [25], with values as high as 120 mPas [138] being reported.

The reduced thermal stability of the tested bioliquids resulted in significant difficulties with deposit formation on the injection nozzles shown in Fig. 7. The reason for this effect is similar as with SVO. However, the chemical composition of the bioliquids with a large content of hydroxyl groups (which often exhibit high viscosity) is even more unstable at elevated temperatures. An additional advantage of air-blast and air-assisted nozzles can be identified in their ability to counteract the high-temperature conditions present in the combustion chamber. With such atomisers, the nozzle discharge surfaces are to a certain extent protected by a layer of atomising air, which serves as a cooling medium that reduces the heat transfer rate from the high temperature primary air. Although this presents an important enabling feature, the vicinity of the flame front and primary zone recirculation eddies causes a substantial radiative heat transfer component as well, which supersedes the connective component by an order of magnitude, hence still requiring other measures to limit the heat transfer from the flame. Proposals for the thermal protection of the nozzle have been given elsewhere [43] and resulted in significant improvement of the deposition rate (shown in Fig. 7d).

3.4.2.2.3. Combustion chamber. Most modern, commercial MGTs use low-NO_x combustion chambers with the prevailing approach being premixing, lean operation, and staged combustion. The first stage of premixing requires either gaseous fuels or fuels that feature a steep evaporation curve and exhibit as little evaporation residue as possible. Thus, to provide a homogenous mixture in the first stage of combustion chamber, bioliquids are not suitable fuels. Consequently, combustion chambers with staged combustion and pre-vaporising tubes have not been proven as suitable for operation with bioliquids yet. In all relevant studies, traditional diffusive combustion chambers are used, although they do not allow for low emission operation with conventional fuels [78,122]. The most significant properties, that were taken into account when developing measures for the reduction of the emission response of MGTs using bioliquids, comprised the evaporation curve, possible evaporation residue, density, surface tension, and viscosity. The following measures proved successful to reducing the fuel impingement on the combustion chamber surfaces:

- A combustion chamber volume increase is the main measure that prevents fuel impingement on combustion chamber surfaces, which was shown to be a limiting factor for the utilisation of highly viscous bioliquids (Fig. 8). A larger volume increases the residence time of droplets [50,139]. These require an extended time interval for their evaporation as they feature low surface to mass ratio and an unfavourable evaporation curve. Although the measure proved successful, a larger volume inherently influences the airflow velocity across the combustion chamber, hence there exists the possibility that this negatively impacts the air momentum and overall flow field in the primary zone. As combustion chambers are carefully designed to provide a strong primary zone recirculation flow that delivers the necessary oxygen in the spray core, an altered flow field might result in increased CO and particulate matter formation rate, unless the adaptations are carried out with a comprehensive underlying optimisation process.
- Elevating the temperature of primary air serves as an add-on to the combustion chamber volume increase. This measure notably promotes heat up and vaporisation of the fuel spray and thus increases the evaporation rate of the utilised bioliquid. At the same time, the aforementioned reduction in air velocity that arises as a consequence of the larger volume, can be compensated by reduced primary air density. Both measures, when combined, partially even out and

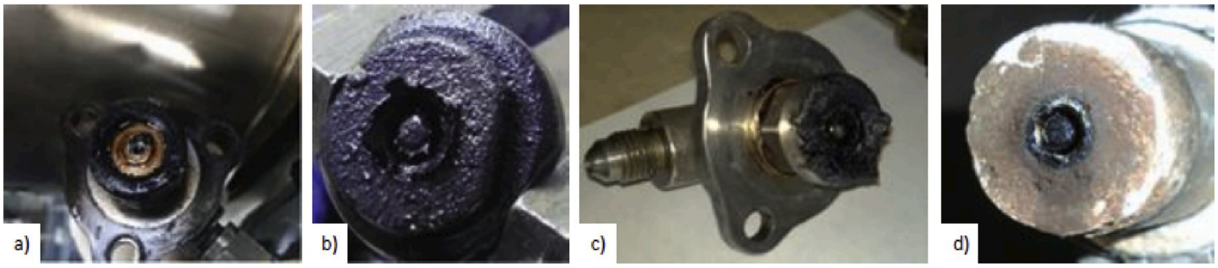

Fig. 7. Injection nozzle deposits after operation with a) 50%/50% FPBO/ethanol blend [128], b) crude liquefied wood [48], c) 50%/50% liquefied wood/ethanol blend [50] and d) improved injection nozzle with crude liquefied wood.

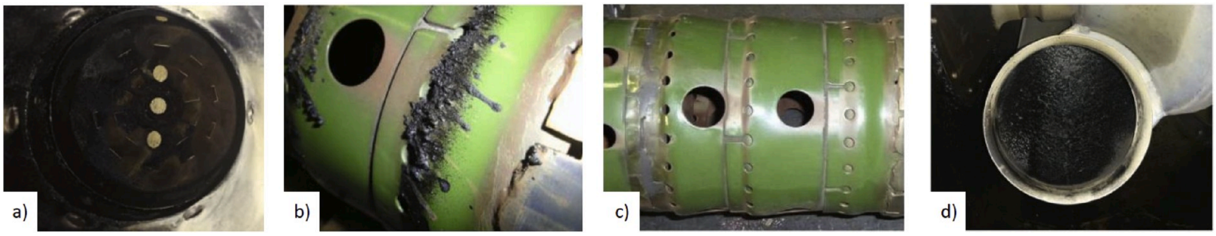

Fig. 8. Combustion chamber deposits with a) 50%/50% FPBO/ethanol blend [67], b) crude liquefied wood in non-regenerative MGT [48], c) crude liquefied wood in regenerative MGT [48] and d) turbine inlet duct deposits with 50%/50% FPBO/ethanol blend [67].

present a key upgrade that enables the use of bioliquids with high viscosity [126]. In Fig. 8c, a notably reduced deposition rate of fuel on the surfaces of the combustion chamber is shown, when the temperature of the primary air is elevated. The drawback of using high temperatures of primary air is perceived through an increased rate of fuel nozzle deposit formation as heat transfer to the injection nozzle surfaces increases along with temperature as well as velocity in the primary zone. To circumvent this challenge, several proposals for thermal insulation of injection nozzles were addressed in sections above.

Taking into account that a high combustion chamber intake temperature is a prerequisite for the successful operation of MGTs with bioliquids [126], modern market-available MGTs that exploit the regenerative joule cycle to maximise effective efficiency can be recognized as an ideal platforms for bioliquid specific adaptations. While this can effectively reduce the complexity of retrofitting, measures to adapt the injection nozzles are still required, and to the knowledge of the authors, no research has been performed in this direction.

3.4.2.3. Engine performance and emissions. The evaluation of engine performance and emissions is done via the close analysis of intermediate combustion products (namely CO and THC) as well as engine-out NO_x and particulate matter emissions. Available research relies mostly on averaged values of pollutants in a pre-specified and stabilised operational point, time-dependant fluctuations of pressure ratios, as well as significant emission species [119]. Despite this, these values can provide an in-depth insight into the state of health of the injection nozzle and fuel homogeneity. In terms of averaged values, currently available studies on highly viscous bioliquids observe a substantial increase in CO emissions along with increased THC emissions [126,136]. In relation to the before mentioned measures, when relying on regenerative MGTs, CO and THC emissions are in all cases reduced, whereas NO_x is increased, mostly as a consequence of a favoured thermal NO_x formation pathway [48]. In line with the properties and composition of feedstock used to produce various bioliquids, increased NO_x emissions were present in cases where the bioliquids exhibited observable nitrogen content, attributed to the presence of fuel bound nitrogen [47]. It is worth noting that bioliquids with high oxygen content exhibited an improved CO - NO_x trade-off in comparison to conventional fuels.

Although there are several underlying factors influencing CO and NO_x emissions in MGTs, the research listed above provides sufficient data to link the CO and NO_x emissions with the power output of MGTs presented in Figs. 9 and 10 respectively.

The reason for the reduction of CO emissions with increasing power output can be traced to the fact that MGTs with higher power output tend to rely on more advanced technology in terms of hot path materials, combustion chamber design, and blade cooling approaches, hence allowing higher turbine inlet temperatures. With FPBO and liquefied wood containing large amounts of cyclic hydrocarbons [45,50] which feature higher autoignition temperatures as well as unfavourable evaporation rates, a high turbine inlet temperature is a major enabler for their utilisation. The data again reveals that bioliquids with high oxygen content exhibit NO_x emissions which are an order of magnitude lower than for example waste trap grease, which usually contains nitrogen carrying species in the form of residual proteins. These observations suggest that if the durability issues are resolved with proper component design, the large benefits of highly oxygenated bioliquids can play an important role in the future of power generation.

4. Future perspective of bioliquids in power generation

By analysing the reviewed research work, it can be concluded that RED significantly increased activities in the area of bioliquids since the vast majority of available studies has been published after 2009, the year when RED came into effect. A significant number of contributions pushed the boundaries of available technology and allowed an extensive investigation of a wide variety of bioliquids in ICEs and MGTs. Along with this, several enabling technical improvements in power generation systems and bioliquid production processes have been developed, thus positioning bioliquids in a highly competitive place within small to medium power generation systems. However, as numerous studies were expanding the knowledge base by providing an insight into various technical aspects, new research topics appeared which require attention. Additionally, new motivation, particularly in relation to a circular economy, improved the position of bioliquids as energy carriers. This opens possibilities for new bioliquids and an increased market uptake of the proposed technical solutions. Thus, under this new perspective, RED II, a careful pinpointing of challenges is necessary to maximise the benefits that power generation with bioliquids could potentially offer to all relevant stakeholders, with a low-carbon society being among the first.

4.1. Role of bioliquids in emerging waste streams

The reviewed production processes of bioliquids represent the most mature approach to convert various bio-based materials into liquid energy carriers. Their key advantage is the transportability of the resulting bioliquids and relative insensitivity to feedstock because of their robust thermochemical production approach. Although the analysed processes mostly rely on conventional materials (lignocellulosic biomass, algae, and waste fats) and they already meet the sustainability criteria, it is highly desired to expand the suitable feedstock to waste streams present in various emerging circular industrial processes, thus exploiting current technical knowledge to expand the benefits of these bioliquids. Therefore, the possibility to swap the feedstock and rely on waste streams with negative cost could improve the economic viability of biocrude production pathways, since several waste streams currently exhibit negative costs due to the fees associated with their disposal.

FPBO can be considered a very promising bioliquid and/or bioenergy carrier, meeting the sustainability requirements of RED II. Due to the relative robustness of the thermochemical conversion process, fast pyrolysis can use a relatively wide spectra of input materials, thus being highly suitable for the use of various feedstock sources such as waste wood, logging residues, contaminated wood, particleboards, etc. This presents one of the main pathways for the future use of residual

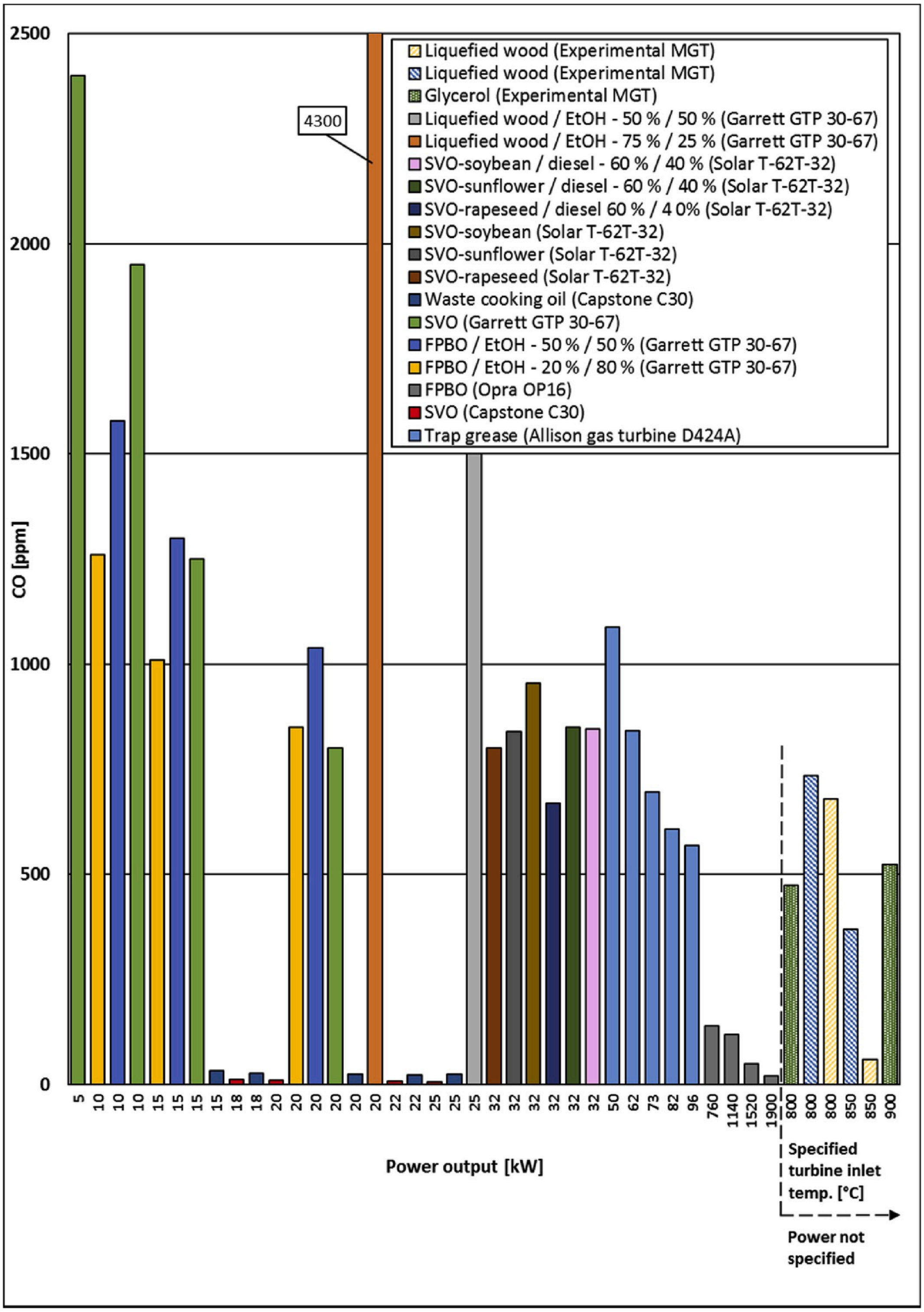

Fig. 9. Relation of CO emissions to the power output of MGTs operating with bioliquids.

materials within a circular economy, extending its applications to several unconventional waste streams that are currently only used as solid fuels for heat generation because of their low moisture content.

Similarly, with different sludges and other waste materials obtained from pulp, paper, and the wastewater treatment industry, a HTL process could employ the high water content in these materials and use it as a solvent. Therefore, feedstock properties that are considered as a drawback in pyrolysis and liquefaction can be turned into technical advantages. By relying on low-quality input materials with high water content, possible gate-fees for their disposal (i.e. 50 - 130 €/t of dry matter for food processing waste and sewage sludge [145]) can be incorporated into any techno-economic evaluation with high potential and almost immediate benefits. This can offset the relatively costly production process whilst increasing the economic advantages of bio-crude to make it competitive to fossil-derived fuels [145].

Moreover, the large potential of liquefied wood as a bioliquid is

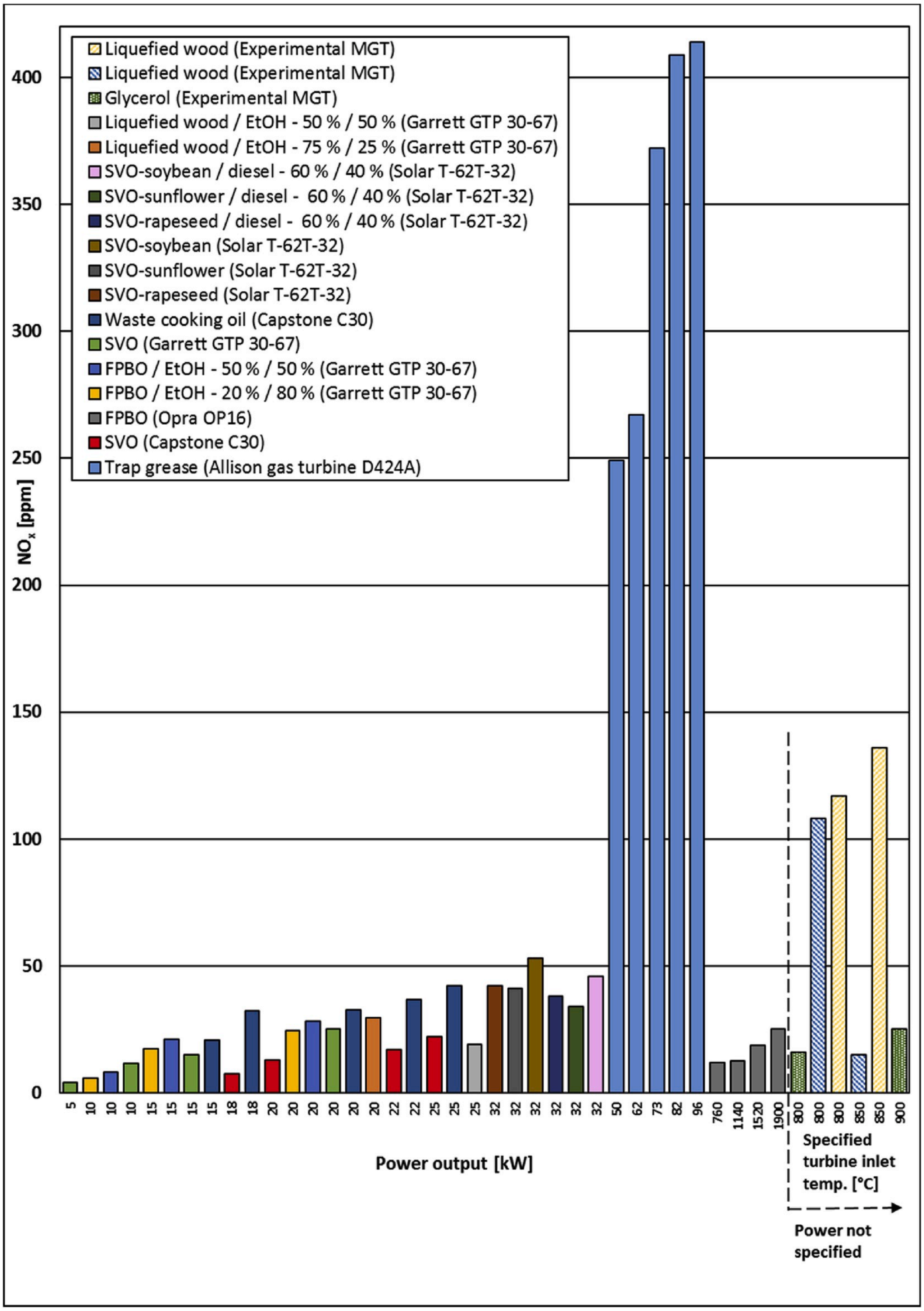

Fig. 10. Relation of NO_x emissions to the power output of MGTs operating with bioliquids.

perceived through its relatively simple production process with inexpensive equipment. The bioliquid cost could become significantly lower and fully economically viable as long as the initial feedstock is obtained as a by-product from other processes. Extensive work has been done with a similar solvolysis process employed in nanocellulose production [42], adhesives [40], and PU foams [146]. Some of the steps in these processes yield waste liquor, which features highly similar properties as liquefied wood [147]. Treating such waste as a bioliquid can exhibit negative prices due to the avoidance of its costly disposal. Similar liquid waste streams also emerge in the pulp and paper industry, for example waste liquor from the Kraft process that could be utilised for power generation in case technology develops further.

For low grade lipid based residuals (notable amounts of these are available throughout food processing industries), which are now used in biogas production plants, a suitable approach could be filtering, cleaning, and subsequent use, similar to the approach used for SVO. Additionally, waste cooking oils are already collected in some urban areas to demonstrate the concept of an urban circular economy. Through this utilisation pathway of waste fats, the relatively high GWP of biogas can be omitted. Although the impacts of biogas substantially differ across the literature, (62 gCO_2eq/MJ [148], 38 gCO_2eq/MJ [149] and 47 gCO_2eq/MJ [150] for combined heat and power applications), typical values for biogas are notably higher than for the aforementioned bioliquids (7–15 gCO_2eq/MJ for FPBO, 9 gCO_2eq/MJ for HTL biocrude. However, a detailed comparison would require extensive dedicated research.

Therefore, both existent and emerging routes for obtaining bioliquids (presented in Fig. 11), reveal that the pathways for their generation do not always follow a linear approach. Instead, several residual streams could potentially be intertwined with recent advances in circular economy and implemented together with power generation. It is worth noting that only with increasing awareness and efforts to promote a circular economy in the past decade, some of these technologies are now under assessment across the globe and RED II might offer a perfect platform to intensify such activities, given properly focused research.

4.2. The challenge of power generation

Research efforts revealed that the technical complexity of different ICE and MGT components and their subsystems is highly dependent on the targeted bioliquid. For example, SVO requires only moderate improvements in fuel preparation and the injection system, leading to promising results on MGTs and even commercially available units based on ICEs. On the other hand, FPBO, liquefied wood, glycerol, and other bioliquids with high viscosity, low volumetric energy density, high oxygen content, and a significantly altered evaporation curve, require several specifically designed adaptations. These comprise preheating system, the introduction of high primary air temperatures, significant improvement of injection nozzles, and an appropriate control strategy. Due to their complexity, such setups are currently only available on the research level and are mostly limited to MGT, as ICEs exhibit major limitations in the injection system.

MGT units, equipped with the listed technical improvements featuring high relative power outputs also exhibit the highest fuel flexibility. For example, certain research-oriented systems are capable of operating with various blends of highly viscous bio-alcohols and fuels obtained through the solvolysis process. The adaptability of such systems is unmatched by ICEs as they exclusively rely on various blends of lighter fuels with bioliquids, even in purely research oriented activities. Despite the technical superiority for the utilisation of bioliquids, the low market share of MGTs apparently prevents the market uptake of power generation with highly perspective bioliquids.

In order to address this challenge, it is best to analyse examples of good practices. A very good example of durable and reliable power generation with bioliquids is the CHP sector that in several cases utilises SVO types that hold little interest for food production in ICEs with sound business cases. The viability of such a combination of a power generation system and bioliquid relies on two major enablers. First is the bioliquid market price (Fig. 12) that helps to ensure a sound business case, while the other is linked to widely available ICE related technical knowledge and the relative simplicity of ICE adaptation to SVO. This is further supported by its inexpensiveness and by large numbers of professionals across the industry that are capable of the implementation of such novelties in ICEs. Such a combination offers the least challenging

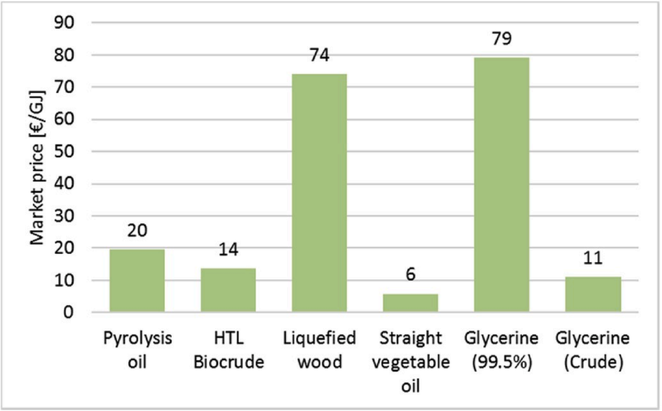

Fig. 12. Current market prices of bioliquids depending on the input materials.

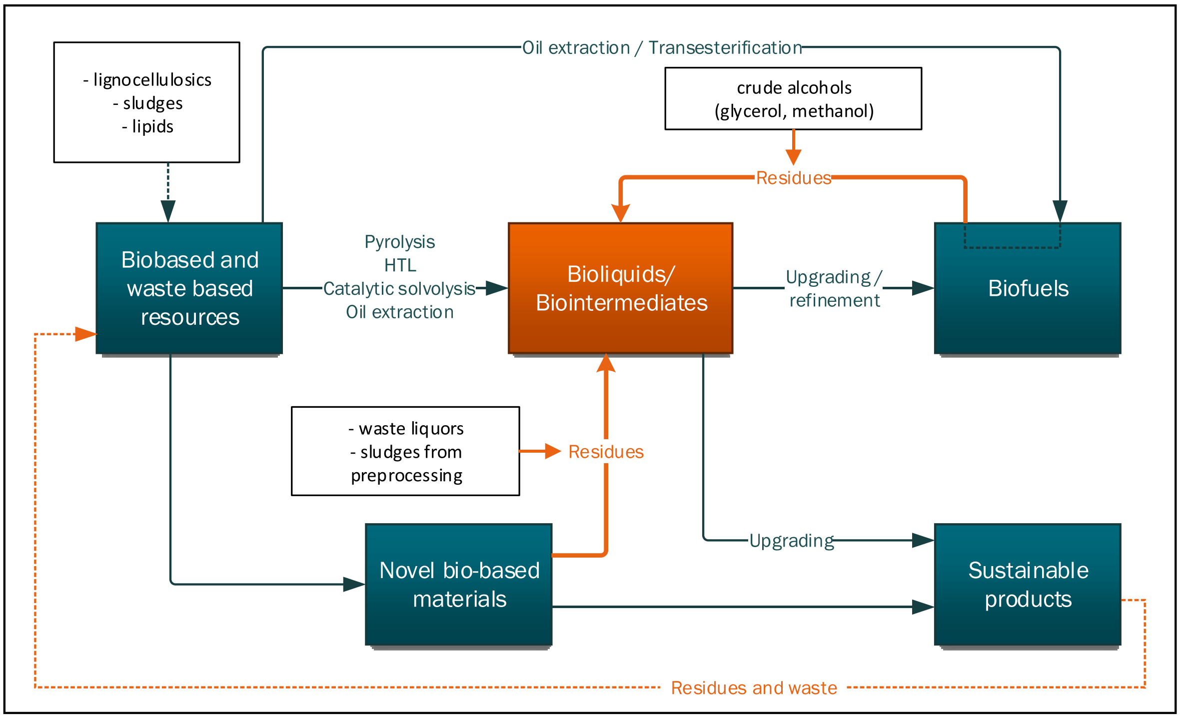

Fig. 11. Future routes for obtaining bioliquids.

approach, which is naturally followed by a non-negligible market uptake of ICE based CHP using bioliquids.

Another example is the utilisation of FPBO in a 2.5 MW gas turbine, developed by a joint venture of Magellan Aerospace and DynaMotive. Although it surpasses the power range of MGT, it shows that the technology is viable but commercially currently not available in MGT based CHP setups. To demonstrate similar achievements as above on a MGT scale for decentralized power generation, the key limitations are a poorly developed MGT market, a lack of general MGT knowledge to foster widespread innovations on a SME scale, and the resulting high ROI of MGT based CHP [73].

From an environmental perspective most of the analysed bioliquids already feature acceptable regulated emission concentrations (CO, NO_x, THC, and in some cases also particulate matter), which, combined with the carbon neutrality of bioliquids, could provide highly sustainable cases for power generation. However, a major concern is the absence of the evaluation of unregulated and possibly harmful species, which can form due to the significantly altered molecular composition of bioliquids in comparison to conventional fuels. Since the legislative framework and reliability of measurement methods are currently still suited for refined fossil and biofuels, a number of species might go unnoticed, and previously unforeseen pathways for the formation of aldehydes and carbonyls might become important.

4.3. *Summary of future technical work*

In order to minimise future risks, an extensive knowledge base arising mostly from the last RED perspective calls for continuous improvements that could seamlessly be undertaken in the upcoming RED II. The research areas with highest potential for impactful solutions can be condensed into the following:

- The atomisation of highly viscous fuels in air-blast atomisers that would enable the prediction of spray distribution, based on the physical and chemical properties of bioliquids. Currently, studies are available only for atomisers designed for continuous combustion devices (MGTs), thus limiting further development of injectors for highly viscous bioliquids in ICEs.
- The bioliquid mixture formation process under high temperature conditions that involves a series of thermochemical transformations, including pyrolysis, carbon residue formation, and possibly also oxidation of solid particles. Currently, such data is available mostly for conventional fossil and biofuels.
- The impact of oxygenated species and high concentrations of fuel bound oxygen on flame-related parameters (i.e. lean extinction limits, temperature distribution, heat release rates, heat flux), which would aid at the combustion chamber design process to reduce the thermal loading of hot path components. Currently, the studies in this area are limited to fuels with a low number of oxygenated groups (i.e. biodiesel, ethanol).
- The interaction of fuel system components with bioliquids in terms of corrosion resistance and appropriate temperature control. For a majority of bioliquids, extensive research dedicated to their interaction with metallic as well as polymer sealing materials is yet to be performed. This will be crucial for obtaining suitable durability of power generation systems.
- The experimental evaluation of unregulated emissions that might contain species previously not present with refined fossil and bio-derived fuels.

The identified areas suggest that the development of power generation with bioliquids is currently not adequately addressed on a fundamental level or is lacking full transferability to higher TRL levels as well as to a larger pool of professionals, leading to large number of studies on a very practical level aiming towards the imminent utilisation of bioliquids. To improve the future transferability of these fundamental results and to enable the appropriate scale-up of current research activities, an improvement in the variability of bioliquids will most likely be required to provide a stable and predictable composition that could be transferred across a range of TRL levels.

If the pace of research efforts stays on a similar level to the one from 2009 up until now, significant improvements in terms of production processes, the utilisation of highly viscous fuels in power generation systems, and the exploitation of unique chemical properties such as a high oxygen content can be expected. Although a knowledge gap is still preventing a full integration of current advances into value chains. To properly position them into a circular economy and make them viable, the multiplication of these effects could prove that improvements done in the area of bioliquids are key enablers for the transition to low-carbon energy generation. Under these conditions, it is fully adequate to continue research activities that will open up new application areas, incorporate them into the latest guidelines of waste management in circular production processes, and thus close the loop of bio-based resources in a modern and effective way.

5. Conclusions

After RED I introduced a separate family of energy carriers –bioliquids– research activities strongly intensified, with the aim of utilising bioliquids for power generation, heating, and cooling. With the present review technical advances, good practices, and approaches to power generation were, for the first time, critically analysed for a wide range of bioliquids. As such, the review presents a foremost holistic and systematic analysis, enriched with insightful technology based comparisons that forms the basis to support an efficient uptake of the introduced RED II. In addition, this holistic and in-depth analysis particularly addresses and interlinks the developed technologies with emerging waste streams and identifies the future role of bioliquids as an important energy carrier supporting a circular economy.

The paper systematically divides bioliquids into two major groups based on their physical and chemical properties. The first group are fuels with properties close to conventional fuels (comprising mostly SVOs) that require less extensive adaptations of ICEs and MGTs, while the second group comprises bioliquids exhibiting high viscosity (FPBO, liquefied wood, and glycerol). The latter bioliquids require extensive adaptations of the fuel supply system, the injection system, as well as control strategies, which limits the application of these bioliquids to MGT based power generation systems. In addition, these fuels also limit the flexibility of system operation in terms of power outputs and in terms of primary air temperature. Although challenging to utilise, highly viscous bioliquids can be produced from low-cost feedstock, which is converted to bioliquids mostly based on thermo-chemical approaches. This opens a significant opportunity for the utilisations of emerging waste streams. Hence, the role of bioliquids supersedes its use solely for power generation and presents a significant opportunity for incorporating them into the processes of a circular economy. Therefore, the review provides the sorely needed link between past efforts, oriented towards the exploitation of bio-based resources for power generation, and the very recent zero-waste oriented society that will require a realistic exploitation plan for residuals originating from intensive material looping.

Finally, the review exposes and discusses several research areas that are opening up opportunities for further technical advances. On an applied level these require in-depth investigation of the atomisation and mixture formation process as well as the interaction of bioliquids with construction materials, while on a fundamental level, the role of oxygenated species in the combustion process and the formation of unregulated emissions should be of high interest. The development of these research areas can further foster the exploitation of unique physical and chemical properties to further reduce the environmental footprint of power generation. With this, a solid basis for the next RED II perspective is set, which is expected to deliver a significant increase in

RES share in final energy use.

Credit

Tine Seljak: Conceptualization, Writing – original draft, Data curation, Visualization, Marco Buffi: Writing – original draft, Data curation, Agustin Valera-Medina: Writing – original draft, Investigation, Data curation. Chong Cheng Tung: Writing – original draft, Investigation, Data curation. David Chiaramonti: Writing – Reviewing and Editing, Investigation, Data curation, Tomaž Katrašnik: Conceptualization, Writing – Reviewing and Editing, Supervision.

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