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Article

A Closer Look at Sustainable Lubricants

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Abstract

Lubricants are used to reduce friction and wear in machines, saving billions of dollars worldwide in energy and breakdown costs and lowering CO_2 emissions. Today, most lubricants are made using hydrocarbons derived from crude oil, which is a finite resource, although alternative bio-based lubricants are also being investigated, as is the re-refining of used lubricants to make new base oil. The CO_2 emissions from current lubricants (due to their manufacture and waste disposal) are estimated and it is found that CO_2 emissions from the production and disposal of lubricants are very much lower than the CO_2 emissions associated with the energy used by those machines. It is also shown that an effective way to make lubricants more sustainable is to extend lubricant oil drain intervals and collect used oil and re-refine it to make base oil for re-use. The role of bio-based lubricants, and their benefits and disadvantages are discussed. Other aspects in which lubricants can be made more sustainable are also briefly covered, such as lubricant packaging, the removal of toxic additives via improved regulatory chemistry, and the use of renewable electricity in blending plants.

Keywords

lubricants, lubrication, friction, wear, sustainability, CO_2 emissions, circular economy

1 Introduction

Many countries are looking to reduce their CO_2 emissions due to their obligations under the UN Paris Agreement [1]. Therefore, options for reducing CO_2 emissions from transport (light duty and heavy-duty vehicles initially), heating and cooling, and other activities (including industry and agriculture) are all being studied by many countries. In the UK, the focus on light duty vehicles is to move to an electrified car fleet, and, at present, it is proposed that the sale of new conventional gasoline and diesel vehicles will be banned from 2030. In addition, there is increased use of biofuels in conventional vehicles, and E10 gasoline is now standard in the UK. There is also great focus within the tribological community on how lubricants and lubrication can be made more sustainable, although in many cases, the environmental impact of current lubricants is often not quantified. Calculations presented here indicate that the CO_2 emissions associated with current lubricants are extremely low, compared to CO_2 emissions associated with the energy used by those machines. Specific examples are given for light duty vehicles and wind turbines. The calculations also suggest that substantial improvements in lubricant sustainability can be achieved by designing lubricants with longer oil drain intervals and collecting used oils for recycling to make new base oils.

Much tribological focus is on the use of bio-derived base oils, and these do indeed have some desirable lubrication properties, but also have issues. Clearly one benefit of bio-derived base oils is that CO_2 absorbed during crop growth can offset CO_2 emissions during the processing of these crops to make lubricant base oil. In addition, bio-derived base oils often have good intrinsic lubricity and low friction coefficients (when the components are in the mixed/boundary lubrication regime). However, there are some disadvantages to bio-derived lubricants, due to the amount of land used for crop growth, possible competition with land used for growing food, or for bio-fuel, the amount of water (another scarce resource) used, and finally, used bio-based lubricants usually need to be treated as hazardous waste, and must be disposed of, or recycled, in a similar way to conventional lubricants.

Other areas that can help improve lubricant sustainability include: (1) the use of renewable electricity (from solar or wind power) at lubricant blending plants, (2) the use of more sustainable packaging solutions for lubricants, and (3) the continued effort to remove toxic chemicals from lubricants via regulatory chemistry authorities. Research is also ongoing into new technologies that may make future lubricants more sustainable, including water-based lubricants, ionic liquids as lubricant base oils or lubricant additives, and the possibility of making lubricant base oils from waste (either biomass or waste plastic).

2 Lubricants and the circular economy

As shown in Fig. 1, there are 17 United Nations Sustainable Development Goals, and tribology/lubricants/lubrication contributes directly to many of these goals, such as good health & well-being (biotribology), affordable and clean energy (via tribology helping machines become more energy efficient), industry, innovation and infrastrure, responsible consumption, etc., and indirectly to others, as further discussed by Ciulli [2].

There is increasing interest, in many industries, in the concept of a "circular economy" in which there is reduced use of resources and resources are re-used and recycled as much as possible.

For the lubricants industry, only a small portion of a barrel of oil (around 1% [3]) is used to make lubricants, with over 80% of the remainder being used to manufacture fuel [3], as illustrated in Fig. 2. There are two ways to look at this. Firstly, if all lubricants derived from oil and gas were banned tomorrow, it would not affect the global demand for oil and gas in any meaningful way. Secondly, if efforts to move consumers from liquid hydrocarbon fuels to alternatives (such as electricity and/or hydrogen) are successful, then the current reserves of oil and gas would last much longer, for products such as lubricants, chemicals, asphalt etc.

Total worldwide annual lubricant usage is approximately 40 million tonnes, and of this, between 0.5-1.0 million tonnes is bio-based, and currently there is re-refining capacity of about 2 million tonnes (Fig. 3). Therefore, there is considerable room for improvement to make the lubricants industry a circular economy, via more recycling of used lubricants and the use of bio-derived lubricant base oils. It should also be mentioned that over the last 20-30 years, many lubricants have been designed to have improved fuel economy (reducing the energy used by machines), oil drain intervals have increased, and in addition sump volumes have often been reduced, despite the trend towards smaller machines with higher power densities. These efforts have helped to improve the circular economy for lubricants by reducing the quantity of fuels and lubricants used in machines.

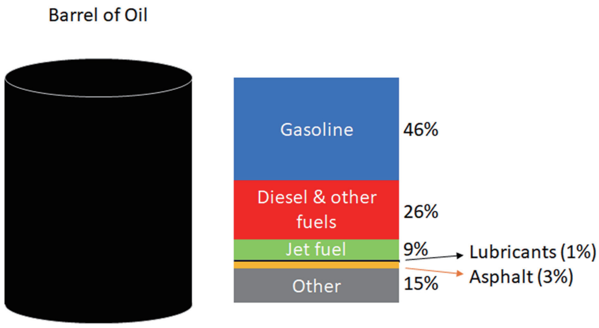

Fig. 2 Breakdown of products from a barrel of oil – the category "other" denotes bottom of the barrel contents which are used to make many varieties of chemicals and plastics.

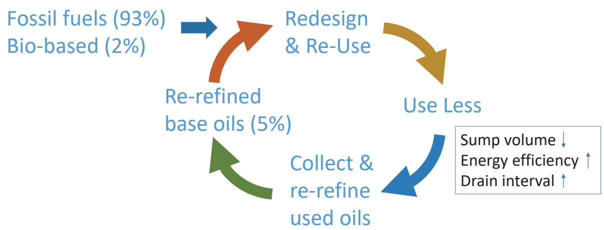

Fig. 3 Schematic of the circular economy for lubricants – 93% of all lubricant base oils are made from new oil (or gas) or bio-based sources. Only 5% of used oil is currently re-refined to make new base oil. Great strides have been made over the last 30 years or so to lengthen oil drain intervals, ensure lubricants are more energy efficient (saving energy used by the machines) and many machine manufacturers have also decreased the size of oil sumps, so less lubricant is used per machine.

Fig. 1 The 17 United Nations Sustainable Development Goals.

3 Lubricants for reduced energy use and extended machine life

The famous Jost report [4, 5] of 1966 on the value of tribology to society was expressed in financial terms but could equally well have been expressed in CO_2 savings. Figure 4 shows the financial savings from the correct application of tribology (using optimized lubricants, employing experienced lubrication technicians, servicing equipment at the right time, etc.) using figures from the Jost Report [4, 5] and contrasting with a much more recent study by Holmberg and Erdemir [5]. Figure 4 shows the interesting differences in the results of these two studies. The Jost Report [4, 5] was written at a time when machines were relatively unreliable, were often run until they broke down and also at a time when energy costs were low, so much of the calculated savings arose from reducing machine breakdowns rather than from reducing friction. On the other hand, Holmberg and Erdemir's more recent 2017 study [6] was carried out at a time when energy prices were high, and machines were much more reliable, so most of the cost savings were predicted to arise from lower friction (leading to lower energy costs). Despite these detailed differences, both studies found that financial savings of about 1.5% of a country's Gross Domestic Product (GDP) could be achieved by good tribological

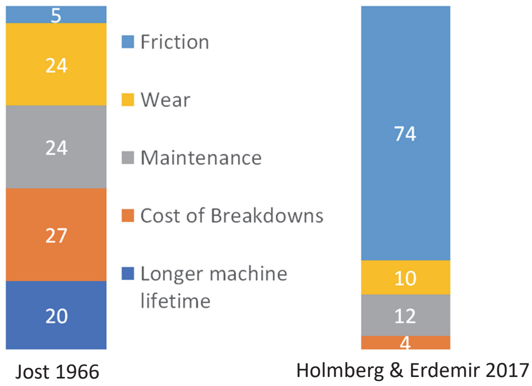

Fig. 4 Breakdown of cost savings (in %) from 1966 and 2017 tribology studies. Numbers on chart show the % saving from the different categories: friction, wear, maintenance, cost of breakdowns and longer machine life. The 1966 Jost study found only 5% of cost savings came from lower friction, whilst the 2017 study of Holmberg and Erdemir found this figure was 74%. The cost savings in both studies equated to approximately 1.5% of the GDP of a country, which today is many tens of billions of dollars.

practices. Since many developed countries today have annual GDP's exceeding 2 trillion dollars, these cost savings are significant. The more recent study [6] also predicted annual CO_2 savings of up to about 3000 $MtCO_2$ from the optimum application of tribology (this is approximately $3x10^{12}$ kg of CO_2 per year). The more recent study [6] also reported that around 23% of the world's energy is used to overcome friction and wear, which is consistent with other studies that have reported figures in the range of 20-30%.

As an example of the impact tribology has had on machine energy efficiency, Table One shows the evolution of passenger car viscosity grade over the last 40 years or so. Taylor [7] has reported that the decrease in fuel consumption would be approximately 5-6%, for a 1990's European 2.0 litre gasoline engine, as viscosity grades move from SAE 15W-40 to SAE 0W-8, although clearly the precise fuel consumption decrease would vary from engine to engine (and some of the lower viscosity lubricants would not be suitable for use in older engines, either). These findings are similar to those of Yamada [8], where a fuel consumption decrease of around 3.5% was reported as the lubricant HTHS viscosity decreased from 4.4 mPa.s to 2.6 mPa.s, for the Sequence VIA engine test. Given that there are about one billion passenger cars in the world, with an average annual fuel consumption of 1000 litres of fuel, total worldwide fuel consumption is around 10^{12} litres of fuel per year. If the move to lower viscosity lubricants has resulted in an annual 5% decrease in fuel consumption, then the average annual fuel saving would be $5x10^{10}$ litres, with a CO_2 saving of approximately $1.5x10^{11}$ kg (since approximately 2.4 kg of CO_2 is released when gasoline is combusted, and another 0.7 kg of CO_2 is released during the extraction of crude oil and the production of 1 litre of gasoline [9]).

4 The CO_2 impact of lubrication

For passenger cars, it has been reported that the combustion of 1 litre of gasoline results in approximately 2.4 kg of CO_2 being emitted [9]. In addition, another 0.7 kg of CO_2 is emitted during the process to make gasoline from crude oil (due to extraction of oil, transportation, and processing) [9]. CO_2 is also emitted during vehicle manufacture, which can be averaged over the vehicle's lifetime. Taking all these factors into account, an average modern European gasoline car has been calculated to have CO_2 emissions of about 223 g/km (assuming a fuel consumption of 6 litres per 100 km, and for such a vehicle, 144 gCO_2/km would come from the combustion of gasoline, 37 gCO_2/km would come from vehicle manufacture, and around 42 gCO_2/km would come from extraction of oil and manufacture of gasoline).

Ishizaki and Nakano [10] have reported that, for lubricants made from mineral base oils, approximately 1 kg of CO_2 is emitted for each litre of lubricant manufactured, of which 0.2 kg

Table 1 Evolution of engine lubricant viscosity grade over time.

	Typical V_k40 (cSt)	Typical V_k100 (cSt)	Typical HTHS (mPa.s)	Approx. viscosity (mPa.s) at -15°C	
SAE 20W-50	144.8	17.8	4.1	5,900	Before 1980
SAE 15W-40	114.3	14.9	3.5	2,900	1990
SAE 10W-30	72.3	10.8	3.2	1,900	1995
SAE 5W-30	57.4	9.9	2.9	1,100	2000
SAE 0W-20	44.4	8.3	2.6	700	2015 onwards
SAE 0W-8	26.1	5.3	1.8	≈ 250	Future

comes from the additives contained within the lubricant. For the more commonly used synthetic lubricants used in most modern passenger cars, it was estimated that 1.65 kg of CO_2 was emitted per litre of lubricant manufactured (with around 0.25 kg of this figure coming from the additives). In addition to lubricant manufacture, lubricants need to be disposed of at the end of their life. Grice et al. [11] have estimated that 1.9 kg of CO_2 is emitted per litre of lubricant disposed of. Therefore, it will be assumed here that, in total, 3.55 kg of CO_2 are emitted due to the production and disposal of 1 litre of lubricant. For passenger cars, the engine lubricant will often have a drain interval of 1 year, and the sump volume is approximately 4 litres. For the transmission oil, it is also assumed that the sump volume is also 4 litres but that the oil drain interval is 5 years. It should be noted that efforts are currently underway in both the US [12] and Europe to develop a "standard" way in which the carbon footprint of lubricants is calculated. In the recently released API Technical Report (TR) 1533 [12] a numerical example is given whereby the carbon footprint of a lubricant of which 50% is recycled and 50% used for combustion is estimated at 1.94 kg of CO_2 released per litre of lubricant. The estimate of 3.55 kg/litre used above where the used oil is disposed of, rather than recycled, can then be seen as a reasonable "upper" estimate to calculate CO_2 emissions for lubricants.

CO_2 emissions can also be reduced by moving away from fossil fuelled vehicles to electric cars, provided that the electricity is predominantly generated renewably. In the UK, with the present mix of electricity generation, it has been estimated that the total CO_2 emissions of battery electric vehicles are still around 88 g of CO_2 per km [13] (of which about 48 g/km is attributed to vehicle manufacture, averaged over the vehicle's lifetime, and the remaining 40 g/km is due to CO_2 emissions from the average UK electricity grid, which is relatively decarbonized, with more than 50% coming from low carbon sources, such as solar, wind and nuclear).

Table Two summarises the calculated annual CO_2 emissions due to the fuel (or electricity) and lubricant for conventional and battery electric cars where it has been assumed that an average vehicle is driven for 16,000 km per year.

Table 2 shows that the total annual CO_2 emissions for a conventional gasoline car are approximately 3585 kg, but only 17 kg of this figure are due to lubricants. Even if there is a move to battery electric vehicles, the CO_2 emissions associated with the electricity used will still be much greater than any CO_2 emissions associated with lubrication.

Similar calculations can also be performed for a wind turbine. A typical 2.5 – 3 MW wind turbine produces about 6 million kWh per year. It has also been estimated [14] that wind turbines produce approximately 11 grams of CO_2 per kWh generated. Table 3 gives official UK government figures for the CO_2 intensity (in grams per kWh) for different types of electricity generation. Table 3 shows that low carbon electricity generated from wind turbines, solar power, and nuclear power, have much lower carbon intensities than electricity generated from coal or natural gas. Despite this, a typical wind turbine will still produce CO_2 emissions of approximately 66,000 kg per year. On the other hand, if it is assumed that 400 litres of lubricant is used in the wind turbine gearbox, and that the oil drain interval is 5 years, the total annual CO_2 emissions associated with the lubricant will only be about 284 kg.

Table 3 Official UK government figures [14] on the carbon intensity (in grams of CO_2 per kWh generated) for different ways of generating electricity.

	Average CO_2 emissions (grams per kWh)
Coal	850
Natural Gas	500
Nuclear	20
Solar Power	75
Wind	11

Grice et al. [11] have pointed out that if used oil were collected and re-used as new base oil for lubricants, the total CO_2 emissions for lubricant manufacture and recycling could potentially be reduced from 3.4 kg of CO_2 per litre (similar to the figure of 3.55 kgCO_2/litre assumed above) to only 0.7 kg of CO_2 per litre of lubricant produced, as shown in Fig. 5. This suggests that one viable route to significantly reduce the lubricant impact on CO_2 emissions would be to design lubricants to have longer oil drain intervals and then collect the used lubricant for re-refining and re-use. This could result in at least a halving of the CO_2 emissions associated with lubrication, from their currently very low levels and would result in a more circular economy for lubricants.

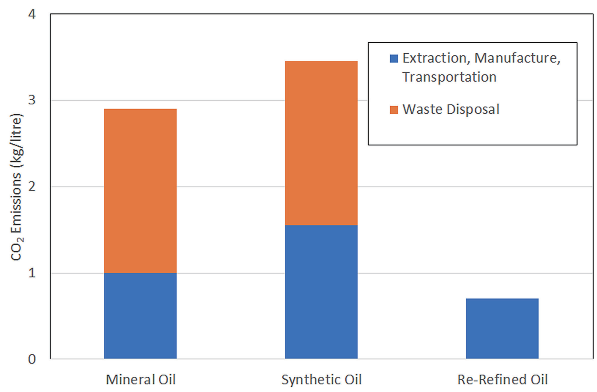

Fig. 5 Approximate CO_2 footprint of lubricants, showing how the use of re-refined lubricants could potentially result in a substantial reduction in lubricant carbon footprint.

Table 2 Comparison of CO_2 emissions associated with the energy used to move the vehicle with those from lubrication of the vehicle.

	CO_2 emissions from energy use (kg)	CO_2 emissions from engine oil (kg)	CO_2 emissions from transmission oil (kg)
Conventional gasoline vehicle	3568	14.2	2.8
Battery electric vehicle	1408	-	2.8

5 Where do bio-based lubricants fit in?

The phrases "bio", "bio-based", "sustainable" and "renewable" are often used loosely and sometimes interchangeably within the tribological community. However, it is possible to have "biodegradable" lubricants which don't contain any bio-derived content and which are not sustainable (examples include lubricants formulated using polyalphaolefin or synthetic ester base oils). In addition, some "bio-based" lubricants may not be biodegradable (according to accepted standard tests). For lubricants, it is only the "readily biodegradable" or "ultimately biodegradable" classifications that are of interest to end customers (and these classifications are based on the performance of the fresh lubricant in standard OECD or CEC tests). Lubricants that contain a certain percentage of bio-derived components can be classified as "bio-based" according to the US Department of Agriculture Biopreferred labelling scheme [15] but may only be classed as "inherently biodegradable" in standard tests, which most mineral oil-based lubricants would meet already.

Biodegradable lubricants are only strictly needed where there is a high likelihood of the lubricant entering the environment. This can happen for example with stern tube lubricants in ships, grease on railway lines, and where hydraulic lubricants are used in forestry equipment. There are various lubricant labelling schemes in place for bio-based or biodegradable lubricants, including the USDA Biopreferred labelling scheme [15], the EU Ecolabel [16], the German Blue Angel ecolabel [17], the Nordic Swan ecolabel [18] and the Japanese ecolabel [19]. In addition, the US EPA Vessel General Permit [20] mandates the use of Environmentally Acceptable Lubricants (EALs) for lubricants used in ships entering US waters, for lubricants that have high likelihood of entering the sea (such as stern tube lubricants) and similar regulations apply in Europe through the OSPAR convention. The main market for biodegradable lubricants has historically been in Scandinavia, and the total market for "bio-based" and "biodegradable" lubricants has been estimated at being between 0.5 and 1 million tonnes annually at present. This is a relatively small, but growing, fraction of the total lubricants market (which is about 40 million tonnes per year).

There are two motivations behind the use of "bio-based" lubricants. Firstly, if base oils can be manufactured from crops that are grown, then those lubricants are sustainable since they are not made using hydrocarbons extracted from crude oil or gas, which are finite resources. Secondly, any CO_2 absorbed by the crops during growth can be offset against any CO_2 emitted during the lubricant manufacturing process. However, it has been reported that large amounts of CO_2 can be emitted if land is cleared to grow crops [21] for use as biofuels, and it can take decades before this initial large release of CO_2 is "paid back". In addition, in some regions, such as Europe, lubricants made from biomass are not considered sustainable if the land could have been used for growing food crops. It has also been reported that large amounts of water (another scarce resource) are used to make biofuels from biomass [22] and similar considerations would be expected to hold for bio-lubricants made from biomass too. Finally, it is worth mentioning that when a bio-lubricant is at the end of its life, the used oil is still considered hazardous in most countries and would need disposing of, or recycling, in a similar way to conventional used oils. There also needs to be some general discussion of whether it makes more sense to restrict the use of biomass to biofuels (where the potential reduction of CO_2 emissions is high) rather than for bio-lubricants (since the previous section has already shown the CO_2 emissions from lubrication are very low compared to those from fuels).

Finally, it is worth noting that base oils used for bio-lubricants will usually be Group III or V base oils. There are currently no industry standard "read across rules" for such base oils. Therefore if a company wishes to make a global engine oil with 30% bio content, then if the crops used for the bio content are different in different regions of the world, all the costly performance engine and laboratory tests required by industry bodies (such as API in the United States, ACEA in Europe, JASO in Japan) would need repeating for each region, which would greatly add to the development costs of such lubricants, and would make such lubricants more expensive. One of the hurdles for customers moving to bio-lubricants is their high price compared to conventional lubricants.

6 More sustainable blending and packaging of lubricants

Lubricant blending plants around the world are starting to make greater use of renewable electricity, often using solar panels or wind turbines. This will reduce the blending plant operating costs and reduce their CO_2 emissions. Some lubricant manufacturers have claimed that over 50% of electricity used in lubricant blending plants now comes from renewable sources [23], and that CO_2 emissions from lubricant manufacturing operations are 30% lower than they were in 2016 [23].

Efforts are also being made to make lubricant packaging more sustainable. Lubricants are now being packaged using recyclable plastic containers, novel "bag-in-a-box" designs, and where possible being delivered in bulk (using for example, re-usable 1000 litre "lube cubes").

7 Removal of toxic additives

One other aspect of lubricant sustainability is to ensure that lubricants are safe to use and free from any components that may cause harm to health. Various regulatory chemistry authorities around the world, including REACH (Registration, Evaluation, Authorization, and restriction of Chemicals) in Europe, TSCA (Toxic Substance Control Act) in the United States, and ENCS (METI) in Japan, classify the various chemicals in use in a range of products, including lubricants, and advise on any adverse health effects from those chemicals. If any chemicals are found to be harmful, the product will need labelling to ensure proper handling, or alternatively, the chemical may cease to be used and alternative, safer chemistries would be substituted.

For lubricants, the following lubricant additives have been removed, or are in the process of being removed from lubricants, due to these regulatory processes: chlorinated paraffins (EP additives) and other chlorine containing additives, tricresyl phosphate (TCP) (historically this was used as a flame retardant and anti-wear additive), tri-tertiary butylphenol (TTBP) (an anti-oxidant), bismuth, antimony and other heavy metals (which have previously been used in grease naphthenates).

8 New technologies

Research is ongoing into the use of water-based lubricants

[24], the use of ionic liquids as lubricants or lubricant additives [25], and the possibility of converting waste (both biomass and waste plastics) into hydrocarbons, for use as fuel or lubricants [26, 27] and research is also underway looking at more sustainable lubricant additives [28]. More work is needed to ensure these different approaches are technically feasible and economically viable. It should be mentioned that most lubricant additives are "used up" during lubricant use (examples include antioxidants, anti-wear and friction modifier additives, dispersants and detergents). However, it is possible that some additives, such as Viscosity Modifiers, could potentially be recovered from used oils and re-used, but it is not known how feasible this would be from both technologically and economically.

9 Conclusions

The rationale for using lubricants is the reduction of friction and wear, and so choosing the optimum lubricant for an application will already contribute to sustainability, since it will enable energy costs to be minimized, and enable long, reliable, machine life.

Over the last 30-40 years, the trend towards lower viscosity grade lubricants, particularly for passenger car engine oils, has resulted in significant fuel savings for OEMs and consumers.

Calculations have been reported that CO_2 emissions associated with lubrication are very low compared to CO_2 emissions from the energy used by those machines. For a conventional UK gasoline car, annual CO_2 emissions were estimated to be 3585 kg, whilst only 17 kg of this figure was associated with lubrication.

The lubricant industry can become more sustainable by (1) extending the oil drain interval of lubricants, (2) using more re-refined base oils, manufactured from recycled used oils, and (3) where appropriate, use bio-derived base oils. These approaches would help reduce the current approximate figure of 93% of lubricants coming from base oils manufactured from crude oil (or natural gas) and would help the lubricants business to become a more circular economy.

In addition, the use of renewable electricity in lubricant blending plants, and smarter, lower impact packaging cam also help to improve lubricant sustainability.

Finally, it should also be mentioned that new technologies currently under investigation, such as water-based lubricants, ionic liquids (either as base oils or additives), and the possibility of making lubricants from waste (such as biomass or single use plastics) are all potential options for making lubricants even more sustainable, although such technologies would need rapid scale up if they are to make a difference before 2050.

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