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The viability and desirability of replacing palm oil

Sophie Parsons[1]✉, Sofia Raikova[2] and Christopher J. Chuck[2]✉

The expansion of palm oil cultivation in recent decades has led to substantial increases in greenhouse gas emissions and biodiversity loss from carbon-rich tropical forest. Because of this, there is increased focus on replacement of palm oil in industrial and consumer products. Plant oils like rapeseed and sunflower oil, exotic oils such as coconut oil and shea butter, and microbial single cell oils have been suggested as potential replacements. Here, we review each of these options from a technical, environmental and economic perspective, including the option to improve the sustainability of existing palm oil cultivation practices.

Palm oil is the most widely used of all major terrestrial oil crops, with over 69 million tonnes produced annually[1]. The market for palm oil is projected to continue expanding at a rate of approximately 2% per year[1]. Palm oil is derived from the ripened mesocarp of the fruits of the oil palm tree *Elaeis guineensis* as crude palm oil (CPO). In addition, palm kernel oil (PKO) may be derived from the inner kernel of the fruit. It is cultivated in tropical regions close to the equator, predominantly in Indonesia, Malaysia, Thailand, Columbia and Nigeria.

Oil palm production competes for space with biodiverse and carbon-rich tropical forest[2]. Expansion of palm oil cultivation into these regions has led to large increases in greenhouse gas (GHG) emissions and significant biodiversity loss. Oil palm plantations are structurally less complex than natural forests, which are vastly richer in species from a wide distribution of taxonomic groups[3]. In addition to this, an estimated increase in deforestation by the end of 2020 of between 3.06 and 4.89 million ha (under business as usual (BAU) assumptions), would result in the emission of an extra 194.8–499.9 $MtCO_2$ (ref. [4]). This is comparable to the total carbon emissions from fuel combustion generated by the countries of Malaysia (216.2 Mt) and Saudi Arabia (527.2 Mt) in 2016[5].

The reason for palm oil's extensive use is twofold: it has the lowest cost (by a significant margin) of all currently cultivated oil crops, and contains a unique lipid profile, being the only vegetable oil to contain an almost 50/50 ratio of C_{16} and C_{18} saturated and unsaturated fatty acids (where C_n denotes carbon chain length) (Table 1). In its unrefined form, palm oil can be used as a cooking oil, biodiesel feedstock, or for chemical synthesis. When used as a food ingredient, palm oil is often fractionated to palm olein (the liquid fraction) with a high oleic acid content and palm stearin (the solid fraction), which contains predominantly palmitic acid.

The main application for palm oil, accounting for 70% of total global use, is as a cooking oil and food ingredient. Palm oil is neutral-tasting and has a smooth texture, which can give food products an appealing mouth-feel, and has a high smoke point, making it particularly useful as a frying oil[6,7]. The melting point for unfractionated palm oil is roughly 35 °C. Additionally, its high oxidative stability contributes to an improved shelf life for processed foods. Palm oil is also used in animal feed for farmed cattle, swine and poultry, as well as pet food. Approximately 8–10 Mt of oils and fats are used annually in animal feed[8]. Increasing levels of palm oil are also being used to produce biofuels. The driver in this sector is mainly price, and there is little benefit to the properties of palm oil biodiesel over any other vegetable oil at the blend levels sold. The other major use of palm oil is in the manufacture of oleochemicals and surfactants for cleaning and personal care products. The largest application for oleochemicals is the production of soaps and detergents, but other applications can include the manufacture of lubricants, solvents, cosmetics, candles, preserving agents, antioxidants and bioplastics, as well as oilfield lubricants and drilling fluids[9]. Lauric acid (C_{12}) from PKO, in particular, is necessary to produce sodium lauryl sulfate (SLS), which is a common ingredient in soaps. In general terms, the price of a feedstock is less important in oleochemical manufacture than the fatty acid properties[9].

As demand for palm oil rises, this is coupled with increasing threats to biodiversity and biogenic carbon release. This has led to increasing calls for palm oil, grown in competition with tropical forest, to be replaced. There are a number of candidates for a potential palm oil alternative. These include other existing crop oils, exotic oils and fats, and single cell oils derived from oleaginous microorganisms such as microalgae or yeast[10,11]. Although the environmental issues posed by palm oil cultivation and processing are well-known and well-publicized, no research to date has compared the feasibility of possible replacements. Here, we present a novel perspective on a pertinent and highly topical issue for agricultural sustainability, crucial to achieving global carbon emissions reduction targets. Potential options for palm oil replacement are evaluated, along with their environmental impact, economic and technical viability, which are drawn together to present a new understanding on the potential for replacing palm oil, and the future direction needed in order to improve environmental sustainability of the oil and fat industries.

Potential alternatives to palm oil

There are a number of potential alternatives to palm oil. These are detailed below.

Existing crop oils. For many applications within the food sector, palm oil could be replaced through hydrogenation of alternative edible oils. Hydrogenation removes unsaturated double carbon bonds through the addition of hydrogen, increasing the melting point of the oil to make it solid or semi-solid at room temperature. Incomplete hydrogenation generates *trans*-fatty acids, which have been demonstrated to be harmful to human health. Full hydrogenation is possible, and the resulting fat contains little if any *trans*-fatty acids or unsaturated fatty acids[12]. However, this is technically challenging, and leads to melting points above body temperature (>50 °C), giving poor mouth-feel and texture for food applications. This can be overcome by using a blend of liquid oils, such as rapeseed or

[1]Department of Mechanical Engineering, University of Bath, Bath, UK. [2]Department of Chemical Engineering, University of Bath, Bath, UK.
✉e-mail: s.c.parsons@bath.ac.uk; c.chuck@bath.ac.uk

Table 1 | Representative composition, yields and production data for palm oil and alternative replacement oils

	Origin	Lipid profile (number of carbon atoms in the fatty acid chain: number of double bonds in the fatty acid chain)					Yield ($l\ ha^{-1}$)	Price (US\$ t^{-1})	Global annual production (Mt)	Global warming impact (kg CO_2e kg^{-1} oil)	References
		Medium chain esters (8:0–14:0)	Palmitic (16:0)	Stearic (18:0)	Monounsaturated (16:1, 18:1)	Polyunsaturated (18:2, 18:3)		Values are from ref. [60] unless otherwise stated.			
Tropical oils	Palm	-	45	5	38	11	5,950	521	75.8	2 (excluding biogenic C) (refined)	11,18,61
	Palm kernel	66	8	2	23	1	500	738	8.8		62
	Coconut	82	-	3	6	2	2,689	724	3.6		11,63
	Babassu	71	8	3	16	1	100–200				64,65
	Jatropha	0	14	7	45	33	1,892	656[66]		8 (refined)	11,66–68
	Shea butter	0	6	41	49	4	0.035	2,700–3,600	0.6	8.2–4.3 (refined)	27,28,69
	Jojoba	0.1	2	4	43	32	1,818	22,000–44,000[70]			70,71
Crop oils	Soybean	0	11	4	22	62	446	745	56.8	2 (refined)	11,18,61
	Rapeseed	0	5	1	61	32	1,190	840	27.2	0.3 (refined)	11,18,61
	Sunflower	0	6	5	20	69	952	719	19.8	0.8 (refined)	18,61,72
	Corn	0	13	3	31	53	172	594	4.5		11,73
	Peanut	0	13	3	38	41	1,059	1,269	5.9	5 (refined)	18,72,73
Animal fats	Tallow	3	27	7	59	2	n/a	683	9.9		73
	Lard	2	27	11	48	11	n/a				73
Other	Used cooking oil	Dependent on the parent oil					n/a	697			
Single cell oil	Phototrophic	0–40	10–60	0–30	0–60	0–60	50,000–150,000	380–6,900 (biodiesel)	0	−0.9 to 5.7 (algae biodiesel)	40,74,75
	Heterotrophic	trace	11–43	1–15	34–74	3–51	~4,000	1,700–8,800 (oil)	0	2.7 (hydro-processed) 3.4 (FAME)	10,41,42, 47,76,77

n/a, not applicable.

sunflower, with a fully hydrogenated fat. For baking, this can give a melting profile similar to that of palm oil[12].

In terms of edible oil volume, soybean, rapeseed and sunflower oil are currently produced in the largest volumes. The annual production of soy, rapeseed and sunflower oils are currently 57, 27 and 20 Mt yr^{-1}, respectively, compared to 76 Mt yr^{-1} for palm oil[13]. As all three are well-established crops, from a regulatory and legislative perspective there should be few challenges to their implementation as a palm oil replacement in manufacturing and food. From a practical perspective, however, replacement has significant implications for land use, especially given the far lower productivity of rapeseed and sunflower crops.

All three oils (soybean, rapeseed and sunflower) are substantially more unsaturated than palm, and have correspondingly different physical properties, the most substantial of which is their liquid state at room temperature. As a result, reformulation is necessary when replacing palm oil with less saturated oils in food products. In many cases, this is technically unfeasible and requires a large research and development (R&D) effort, including the need for additional viscosity modifiers.

Genetically enhanced versions of sunflower or rapeseed oil, which produce high proportions of oleic and stearic acid, could also present a viable route to palm oil replacement. Targeting saturated fatty acids like stearic acid could eliminate the need for vegetable oil hydrogenation. Sunflower mutants with high stearic acid have been isolated through mutagenesis and classical breeding[14]. These high-stearic and high-oleic oils could be an alternative to palm or exotic oils used in confectionery production[14], as they better mimic some of palm oil's properties and fatty acid profile (Table 1). A high oleic acid content also improves oxidative stability for frying. These palm alternatives are most commonly found on the market as high-oleic sunflower and high-oleic rapeseed oil.

For fuel use, where the market is dominated by price considerations, soya or rapeseed oil could be used to displace palm oil, although the fuel properties of the resulting fuels will differ slightly. The cetane number (indicating ignition properties), heat of combustion, melting point and viscosity of neat fatty compounds all increase with increasing chain length and decrease with increasing unsaturation of fatty acid methyl esters (FAMEs), so the structural fatty acid composition of different oils has an impact on the physicochemical properties of biodiesel[15]. However, the composition of the initial feedstock for hydrotreated vegetable oil (HVO) biofuels produced through catalytic decarboxylation will not strongly affect fuel properties.

For surfactant applications, fatty acid profile is more important, and reformulation will be necessary in order to emulate the consistency and behaviour of palm oil in cosmetics using oils with a different fatty acid profile. This is likely to incur a cost penalty, as all other cultivated oil crops are currently less productive and more expensive than palm oil. Hydrogenation of unsaturated vegetable oils could bring their physicochemical properties more in line with those of palm oil, and therefore necessitate less extensive reformulation.

Given the environmental impacts associated with oil palm cultivation, the regions in which crop alternatives are cultivated are also important to consider. This avoids the risk of environmental burden shifting from one part of the world to another. For instance, soybean is cultivated in similar climatic zones to palm, but at higher latitudes. The largest producer of soybean is the United States, with Brazil and the Amazon region a close second[13]. This means cultivation carries with it similar implications for biodiversity loss and life cycle emissions associated with deforestation for large-scale cultivation. In addition, soybean has a substantially lower oil production per hectare (446 l ha^{-1}, compared to 5,950 l ha^{-1} for palm). Rapeseed is widely cultivated across Europe and the United States, Canada, China, India and Australia, whilst the largest producers of sunflower oil are Ukraine and Russia, followed by Argentina, China and Romania. Both crops have the capacity for cultivation to be expanded without destroying high-carbon stock tropical forest, although the oil yields per hectare are again vastly lower than that of palm (1,190 and 952 l ha^{-1} for rapeseed and sunflower, respectively). Owing to their lower per-hectare yields, soybean, rapeseed and sunflower oil all have higher costs per tonne than palm oil (Table 1).

The comparative environmental impacts of various edible oils including palm have been explored by several authors[16–18]. When considering a number of different impact assessment categories alongside global warming potential (GWP), rapeseed oil is not entirely environmentally preferable to palm oil due to the high levels of fertilizer used during the cultivation of oilseed rape[17]. For HVO biofuel production, using palm oil mill effluent (POME) to produce biogas, rather than leaving it in open ponds that release methane into the environment, led to a lower GWP associated with palm oil than with rapeseed[16]. A more recent study comparing the consequences of edible oil substitution showed that replacing palm with a global mix of other edible oils could reduce GWP by 522 kg CO_2e per tonne of oil[18]. Peanut oil production has been reported to have the highest GWP compared with palm, soy, rapeseed and sunflower oil[18] (Table 1).

Based on the findings of these life cycle assessment (LCA) studies, there is no clear-cut argument for an optimal palm oil replacement using alternative terrestrial oils from an environmental perspective, given the significant uncertainties attached to modelling agricultural impact—particularly the use of fertilizer (rape and sunflower) and peat soil (palm). From an economic perspective, in 2018 the average cost of palm oil per tonne was much lower than that of sunflower or rapeseed oil[19]. For food, this would need to be considered alongside R&D costs associated with reformulation.

For biodiesel and oleochemicals, waste cooking oil and animal fats (for example, beef tallow) typically have a lower GWP than rapeseed or soybean (and hence palm) biodiesel[20]; however, most studies do not fully account for land-use change[21]. Tallow is preferred under both US and European biofuels regulatory frameworks, but constitutes only roughly 4% of total world oils and fats production by volume, and is constrained as a by-product of beef production[22]. In addition, almost all available animal fat is now used as a feedstock for biodiesel production[22]. For these reasons, animal fats cannot be considered a long-term, large-scale alternative to palm oil.

Alternative tropical oils. Alternative tropical oils, such as coconut or babassu, have similar fatty acid profiles and physicochemical properties to palm oil, making them more suitable than crop oils for use as direct replacements of palm oil. However, they are currently substantially less productive and more expensive than palm. As they are also cultivated in a similar geographic region, an increase in the intensity of cultivation will result not only in higher carbon emissions, but also in similarly severe impacts on biodiversity through land-clearing and deforestation.

For food applications where fatty acid profile is important, coconut oil is a suitable palm oil substitute, although it has a somewhat lower melting point (25 °C, compared to 35 °C for palm oil), which would necessitate some degree of reformulation. Additionally, it is more highly saturated, which would have negative implications for the nutritional value of the food products. Coconut oil has a near-identical fatty acid profile and therefore similar physical properties to PKO, so could be used as a direct replacement in food applications where PKO is currently utilized.

Other tropical oils, such as jatropha, jojoba and babassu, are non-edible, and are therefore better suited for use as palm oil substitutes in fuel and oleochemical applications. Jojoba and babassu oils are already used in cosmetic and personal care applications, although the price points are somewhat higher than that of palm (Table 1). For fuel applications, alternative tropical oils would be highly suitable. A blend of babassu and coconut oil was successfully used to generate biodiesel for a Virgin Atlantic test flight in 2008[23]. Babassu oil biodiesel has been shown to fulfil specifications for moisture, specific gravity, kinematic viscosity, free alcohol content and free glycerol for biofuels[24], although it has yet to be commercialized. Jatropha oil is regarded as one of the most promising options for biodiesel production in tropical countries, and has been calculated to have lower GWP compared to other biodiesels[25]. Its fatty acid profile is dominated by monounsaturated oleic and linoleic acids, which gives better cold flow properties relative to palm biodiesel. Jojoba oil has also been a promising candidate for fuel production[26]. However, the cost of raw materials, especially feedstock, accounts for the majority of the cost of biodiesel production, irrespective of technology type, so alternative tropical oils are unlikely to be competitive with palm from an economic perspective (Table 1).

The environmental impacts of edible exotic terrestrial oils and fats, such as coconut oil and shea butter, have been explored far less extensively than other terrestrial oils. Shea is a tree crop indigenous to sub-Saharan Africa, predominantly found in Nigeria, Mali, Burkina Faso and Ghana. It is estimated that 600,000 t are produced in Africa per year; between 150,000 and 350,000 t are exported[27]. Shea butter itself can cost US\$2,700–3,600 t^{-1}, but export to the United States can cost as much as US\$13,000 t^{-1} (ref. [27]). Shea butter production equates to a GWP of 10.4 kg CO_2e per kg of refined shea butter for cosmetics[28]. Overall, the high price of shea, coupled with its small production scale, makes it challenging to replace palm oil on a scale any higher than niche cosmetic products and small-scale food applications. Shea, along with coconut, argan and other exotic oils, also has limited capacity to increase dramatically in market volume without incurring the same environmental and social impacts associated with palm production[29].

Single cell oils. Alternatively, microbial oils—termed single cell oils (SCOs)—could be used instead of terrestrial plant oils. SCOs are edible oils produced from microalgae, yeasts, fungi or moulds. A number of these microorganisms are known to accumulate high levels of lipid within the cell, typically around 40% of total cell mass, with accumulation of up to 70–80% previously reported[30]. These oleaginous species can produce an oil analogous to those generated by terrestrial plant oils, composed of predominantly palmitic, stearic, oleic and linoleic acids. However, the lipid profiles of oleaginous microorganisms can be honed through adjusting culture conditions, and a desirable fatty acid content achieved from yeast or algal strains, with or without genetic modification (Table 1).

For biodiesel applications, phototrophic algal species have been extensively researched for the past 50 years, spurred by the first oil crisis in the 1970s. It has been claimed that microalgae can produce 30 times more oil per unit area of land than oil crops[31]. The US National Renewable Energy Laboratory (NREL) has focused much attention on lipid production from phototrophic microalgae, demonstrating production in large 1,000 m^2 pond systems. However, contamination from other pervasive local species, issues with organism robustness, and elevated downstream processing costs made the produced biodiesel prohibitively expensive[32].

Alternatively, heterotrophic microalgae such as *Crypthecodinium cohnii* are used in the commercial production of docosahexaenoic acid (DHA), an omega-3 fatty acid used most notably in baby formula. The oil is commonly associated with fish oils and the health benefits they provide. The high value of DHA oils compared with other shorter-chain fatty acids, and the lack of a terrestrial oil equivalent (plants do not synthesize long chain polyunsaturates up to a 22-carbon length), has enabled this particular SCO to be a commercially viable entity.

Other heterotrophic oleaginous species include the yeasts *Lipomyces starkeyi*, *Yarrowia lipolytica*, *Cryptococcus curvatus*, *Cryptococcus albidus*, *Rhodotorula glutinis*, *Rhodosporidium toruloides* and *Trichosporon pullulans*. These are well-documented for their potential to produce SCOs suitable for use in food, oleochemicals and biodiesel. Lipid accumulation in yeasts typically occurs in nitrogen-limited environments, where the carbon flux in the cell is diverted from energy production to lipid (triacylglyceride, TAG) synthesis[33], though recent work has sought to decouple this mechanism, allowing more rapid lipid accumulation[34]. Yeasts are able to metabolize a large variety of raw materials, including C_5 and C_6 sugars derived from lignocellulosic feedstocks[11]. To date, the highest confirmed values for lipid productivity are 1–1.2 g l^{-1} h^{-1} (refs. [35,36]).

Industrially, a heterotrophic algae-derived butter and oil was produced by TerraVia (owned by Corbion). Other previous food application research has demonstrated that SCOs are suitable for use as cocoa butter equivalents (CBEs). Here, production was demonstrated at the pilot scale, but at the time deemed not economically viable given the low cost of cocoa butter[37].

The robust nature of oleaginous yeasts and algae, and their ability to grow on a wide variety of substrates as well as C_5 and C_6 sugars (including lignocellulosic wastes and other sugar-rich waste feedstocks) make them a potentially important replacement for terrestrial oils. The breadth of SCO fatty acids produced (from short to mid-chain saturates to monounsaturates and linoleic acid) far outweighs that which can be achieved even with genetic modification of terrestrial oil crops. Importantly, as the physical properties of palm oil are solely related to its lipid profile, this means that there is a real potential to be able to match the exact properties of palm oil using oleaginous microbes. As such, SCOs could provide a direct replacement to CPO, palm stearin and palm olein, as well as PKO. For surfactants or biodiesel, unlike tallow and waste cooking oil, SCOs are not a constrained by-product. For food applications, SCOs avoid the need to reformulate, hydrogenate or use expensive exotic oil blends, as they can be tailored to imitate the fatty acid profile of palm. Despite these benefits, the use of SCOs as a direct substitute to palm oil faces key technical challenges, which ultimately affect their commercial viability.

For example, phototrophic organisms cultivated in large open ponds do not have the productivity required for feasible economic deployment, as the yields are far too low, and the cost of drying outweighs the benefit. In addition, the open nature of the ponds means they are vulnerable to invasive species, and strains often lack robustness against fluctuating environmental conditions, and, as such, contamination is a key concern. Alternatively, while heterotrophic organisms can grow two magnitudes more densely than phototrophic organisms, the large stainless-steel stirred tank bioreactors used for heterotrophic fermentation are size-constrained to allow for effective aeration (an important distinction between the fermentation of microorganisms for SCO, and the fermentation of *Saccharomyces cerevisiae* for beer or ethanol production). This is associated with higher capital expenditure and operating costs. As such the projected cost of SCOs is far higher than palm, making them less economically desirable.

Both phototrophic and heterotrophic organisms produce SCOs intracellularly, necessitating unit processes further downstream to homogenize and release lipids from the cell. These additional processes further increase capital and operating costs, as well as reduce overall efficiency. Many of the additional costs are unknown due to system performance uncertainty at scale. This adds high risk to investors operating outside of the high-value chemicals space, reducing the feasibility of gaining investment required for full industrial operation.

Palm is the lowest-cost terrestrial oil, and hence any industrial biotechnological process aiming to compete with palm faces an additional barrier in making alternative oils economically competitive. The market for sustainability or palm-oil free credentials may allow for some flexibility in price, but permissible price increases would typically be limited to around 10%[38]. The use of palm oil in various food products, from frying oils to shortenings in baking, is complex and requires a range of saturates and monounsaturated fatty acids. Ultimately, SCOs are the sole route to an alternative that can closely match the fatty acid profile of palm oil, whilst avoiding cultivation of crops in tropical regions. For surfactants and biodiesel, the breadth of TAGs, free fatty acids and fatty alcohols offered by SCOs makes them a promising platform for a palm oil replacement.

The sustainability of SCOs has primarily been assessed in terms of biodiesel production, with less emphasis on food or oleochemical applications[39]. For biofuel production, this predominantly relates to phototrophic organisms. The ability of microalgae to utilize waste CO_2 from industrial processes, along with waste nitrogen and phosphorus from wastewater, makes it highly interesting from a sustainability perspective. GWP estimates for microalgal biofuels range from 0.7–5.7 kg CO_2e kg^{-1} (Table 1), and economic cost estimates vary between US\$1.64–30 gal^{-1} (ref. [40]). These large ranges stem from substantial variability in the definition of system boundaries and productivity assumptions (lipid productivities can range between ~10–120 m^3 ha^{-1} yr^{-1})[40]. Another factor that can interfere with accurate assessment of economic or environmental feasibility is the use of extrapolation from laboratory data to large-scale processes, often leading to unrealistic assumptions being made.

Far fewer studies have investigated sustainability relating to heterotrophic organisms[41–46]. In terms of economic costs, these range from US\$1.7–8.8 per kg oil product[41,44,47]. These costs are sensitive to variable operational costs including feedstock price, fermentation productivity and capital investment. GWP is roughly 3 kg CO_2e kg^{-1} (Table 1). This is dominated by impact from feedstock or fermentation aeration/mixing.

Replacing palm oil

Palm oil is low-cost, associated with high productivity per hectare, and has a high complexity in the way that it is used within product formulations. From a technical perspective, achieving a direct replacement for palm oil is more straightforward for certain applications than for others. For example, although biodiesel is comparatively feedstock-agnostic, the large-scale replacement of palm oil in food and oleochemicals is technically challenging, with alternatives currently lacking a strong environmental narrative and economic viability. In food applications, high-oleic vegetable oils for frying have been demonstrated to achieve similar properties to palm olein without hydrogenation[48]. Frying for domestic use brings in additional challenges associated with consumer behaviour change, as opposed to changes made within the product supply chain supported by direct market drivers or policy. For more complex applications, requiring palm stearin or CPO, direct replacement with vegetable oils alone cannot be accomplished without reformulation or blending with exotic fats like shea butter. Although such blends can replace the palm oil mid-fraction, they require tempering and may still necessitate significant product reformulation in order to avoid recrystallization at room temperature and fat bloom (separation and re-solidification of fat at the surface)[12]. These changes are also all more expensive than palm oil, and all substitute for lower-productivity crops, with exotic oils currently nowhere near the production volumes needed for blending.

Are SCOs a potential long-term replacement?. From a product perspective, SCOs have been shown to produce oils with identical lipid profiles to that of palm oil[49]. This gives the oils almost identical properties to palm. While phototrophic algal oils have been widely dismissed as technically unfeasible, heterotrophic SCOs have gained a large amount of recent attention, with industrial-scale production clearly demonstrated. However, despite expected technical advances over the short term, it is likely that SCOs will remain at least 2–5-times more expensive than CPO[41,47]. These processes also need an extremely high capital investment for even modest-scale plants. This raises serious concerns over the practicality of developing wide-scale SCO replacements for lower-value edible oils. Nevertheless, this cost could be outweighed by the environmental benefit of cultivating the SCOs on lignocellulosic residues and other waste resources, resulting in vastly reduced impact on existing natural resources and localized production, which could be tailored for each specific market need.

For biofuels, the revised European Union (EU) Renewable Energy Directive (2009/28/EC)[50] means that fuels which count towards the advanced biofuel target of 3.5% by 2030 can expect to be eligible for either direct or implied subsidies. Phototrophic algae cultivated in open ponds are included in the list of eligible feedstocks. This means that subsidy support within the EU could improve the economic viability of phototrophic processes in the future. The prospects for heterotrophic cultivation of SCO biodiesel, however, are less clear, though would presumably still fall within this remit as long as the sustainability of the feedstock was assured.

Sustainability in the short to medium term. An alternative to palm oil replacement is to improve the sustainability of the current palm oil production paradigm. The main non-state, market-driven governance system through which sustainable production of palm oil can be assessed is the Roundtable on Sustainable Palm Oil (RSPO), with roughly 19% of global palm oil production classified as Certified Sustainable Palm Oil (CSPO)[51]. There has been some criticism of RSPO and CSPO over the years. Most substantial criticisms centre on the lack of a CSPO market (leading to supply of CSPO outstripping demand); the inability of RSPO as an organization to enforce its Principles and Criteria (P&Cs); ambiguous interpretation of the P&C documentation; and lack of a 'fuller-systems' perspective from a plantation- and mill-oriented certification scheme[52,53]. In 2018, the RSPO adopted the High Carbon Stock Approach, which brings it in line with no (or zero) deforestation policies and commitments. These are now in place and strengthen the RSPO's commitment to no deforestation[54]. A new smallholder standard has also recently been developed in 2019[55]. Given the current shortcomings of alternatives, particularly the prohibitive cost of SCOs at present, effective policy and market-based approaches that push sustainable palm oil forward are key in the short to medium term. Given the economic and social significance of palm oil in palm oil-producing regions (such as Indonesia and Malaysia), efforts to retain their right to self-determination should not be downplayed. Firstly, approaches must include greater national (in palm-producing countries) and international effort to create demand for CSPO, particularly in India and China, where palm oil use is increasing, with care taken that this does not lead to leakage of palm oil into un-tariffed markets. This should be accomplished through implementing incentives (for example, reduced transaction costs of switching to sustainable products) alongside any penalty system[56]. Secondly, with the RSPO's strengthened P&Cs with respect to deforestation, cultivation on high-carbon peatland, and worker exploitation, focus must now be on enforcement, and tightening any remaining gaps. Thirdly, plantation- and mill-level certification must go hand-in-hand with sustainability efforts at a wider regional and international level. This includes ensuring regional and national policy mechanisms are in place to prevent further expansion onto high-carbon stock land, and that based on full life cycle considerations, appropriate actions are in place that target key environmental impacts[57].

In addition to improved enforcement of P&Cs and peatland cultivation, better waste management practice at the milling stage has been identified by many authors as key to reducing climate change impacts[16–18,58]. This relates specifically to the management of empty fruit bunches (EFBs) and POME. Composting and methane recovery have been shown to yield substantial reductions in environmental impact[58]. Palm oil producer Neste estimates that 70% of palm oil mills in Indonesia and Malaysia do not have any methane reduction measures in place[59].

Overall, technology and policy improvement is recommended over substitution. Of course, this is aside from the case of biodiesel, where, rightly, alternative second- and third-generation feedstocks are encouraged, with a possible role for POME in future biofuel generation. Whilst the RSPO works to enable best practice to reduce cultivation and mill-related impact, particularly now where they specifically target deforestation and cultivation on peatland, this may not result in significant impacts unless changes are made. There must be regulatory or economic drivers towards adopting more sustainable practices, and challenges relating to enforcement need to be resolved. Despite LCA evidence showing clear potential for environmental impact reduction, systems-level changes are required in order to make this a reality.

Conclusions and outlook

The unique fatty acid profile and low price of palm oil makes it challenging to replace. For certain applications, direct replacement could be possible using existing conventional oils; however, this is not an option when the saturated fats and oils are key to product formulation. There is neither an economic nor an environmental case for the substitution of palm with vegetable oils or exotic oils on a large scale. This leaves two remaining options: the substitution of palm oil with single cell oils from yeast or microalgae, or more effective implementation of schemes to ensure sustainable palm oil production.

SCOs, with their tuneable lipid profile, offer the most promising technical solution as a direct alternative. Whilst initial capital costs and low productivities currently prohibit serious investment in this technology, clear demonstration of environmental benefit and robust policy support (as an advanced biofuel, for example) could create a clear route for SCOs to become a viable palm oil replacement in the future.

In the short to medium term, ensuring sustainability in the palm oil sector is the only realistic approach to reducing environmental impact. This requires going beyond existing voluntary certification schemes, and accounting for supply chain complexity and sociopolitical challenges. This can be achieved through engagement with stakeholder groups, and national and international communities. Desire to increase market demand for CSPO must move beyond simply shaming palm oil-producing companies into taking action—the drive towards this must come from policy incentivization. These actions should go hand-in-hand with effective monitoring strategies (for example, remote sensing) to ensure a halt to deforestation.

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Competing interests
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Additional information
Correspondence should be addressed to S.P. or C.J.C.

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