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SPECIAL FEATURE: REVIEW ARTICLE

Synergies and Trade-offs between Sustainable Development Goals and Targets

Impact of Malaysian palm oil on sustainable development goals: co-benefits and trade-offs across mitigation strategies

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Abstract
Palm oil (PO) is an important source of livelihood, but unsustainable practices and widespread consumption may threaten human and planetary health. We reviewed 234 articles and summarized evidence on the impact of PO on health, social and economic aspects, environment, and biodiversity in the Malaysian context, and discuss mitigation strategies based on the sustainable development goals (SDGs). The evidence on health impact of PO is equivocal, with knowledge gaps on whether moderate consumption elevates risk for chronic diseases, but the benefits of phytonutrients (SDG2) and sensory characteristics of PO seem offset by its high proportion of saturated fat (SDG3). While PO contributes to economic growth (SDG9, 12), poverty alleviation (SDG1, 8, 10), enhanced food security (SDG2), alternative energy (SDG9), and long-term employment opportunities (SDG1), human rights issues and inequities attributed to PO production persist (SDG8). Environmental impacts arise through large-scale expansion of monoculture plantations associated with increased greenhouse gas emissions (SDG13), especially from converted carbon-rich peat lands, which can cause forest fires and annual trans-boundary haze; changes in microclimate properties and soil nutrient content (SDG6, 13); increased sedimentation and change of hydrological properties of streams near slopes (SDG6); and increased human wildlife conflicts, increase of invasive species occurrence, and reduced biodiversity (SDG14, 15). Practices such as biological pest control, circular waste management, multi-cropping and certification may mitigate negative impacts on environmental SDGs, without hampering progress of socioeconomic SDGs. While strategies focusing on improving practices within and surrounding plantations offer co-benefits for socioeconomic, environment and biodiversity-related SDGs, several challenges in achieving scalable solutions must be addressed to ensure holistic sustainability of PO in Malaysia for various stakeholders.

Keywords Palm oil · Biodiversity · Poverty · Health · Sustainable Development Goals · Mitigation

Introduction

The African oil palm (OP) *Elaeis guineensis* is a vital source of edible oil, derived from its mesocarp and kernel. Malaysia (26%) and Indonesia (58%) are the largest global palm oil (PO) producers, which together accounted for 84% of globally produced PO in 2021 (USDA 2021). These countries are also global emerging economies that belong to the world's biodiversity hotspots (Myers et al. 2000). Hence, while the rise and expansion of OP as a cash crop has fueled the industry and economy (Qaim et al. 2020; Karki et al. 2018), it has come at significant costs to the region's rainforests and biodiversity (Qaim et al. 2020; Vijay et al. 2016), including violations of land rights towards indigenous peoples (Buckland 2005; Sheil et al. 2009). These drawbacks have led to

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calls for boycotts, anti-PO campaigns and governmental policies, particularly from the European Union, North America, Australia, and New Zealand (Walden 2019). Additionally, the use of PO is debated due to perceived and documented adverse effects on human health, both on nutritional aspects of widespread dietary consumption, and societal aspects in terms of rights of workers and local communities living in plantation landscapes (Qaim et al. 2020).

Arguably, any crop that is cultivated unsustainably inflicts damage to ecosystems and biodiversity due to deforestation, excessive fertilizer usage, pesticide runoffs and negative effect of monocropping on soil and ecosystem resilience (Asher 2019). This was seen in the cultivation of other major crops, such as the rampant deforestation for cattle soy-feed in the Amazon between 1996–2005 or the toxic algae bloom of Lake Erie in 2014 culminating from decades of pesticide and fertilizer runoff from corn crops (Macedo et al. 2012; Nepstad et al. 2014). However, blanket measures to address negative impacts of PO production may undermine the complexity of issues surrounding OP cultivation and the PO industry, and hamper concerted international efforts towards achieving various Sustainable Development Goals (SDGs) (Hinkes and Christoph-Schulz 2020).

While negative impacts of excessive consumption and unsustainable agricultural practices seem indubitable, what constitutes as sustainable practices and their ability to mitigate associated negative issues is less well-defined, exposing significant knowledge gaps in efforts to develop more effective sustainability policies for PO. Thus, this review aims to (1) summarize the available evidence on the impact of PO production and consumption on human health, social and economic aspects, environment, and biodiversity in the Malaysian context, and (2) discuss efforts to mitigate negative impacts and identify SDG-related co-benefits and trade-offs of different mitigation strategies.

Impact of Malaysian palm oil

The impact of PO was summarized based on a systematic search using PRISMA (http://www.prisma-statement.org/) guidelines, with manual addition of relevant contextual articles and reports resulting in a total of 276 full texts reviewed (Supplement, Figure S1). The various impacts of PO were categorized broadly under health, socioeconomics, environment, and biodiversity (in the Malaysian context), and then mapped to specific SDG keywords (Fonseca et al. 2020).

Nutritional impact of palm oil consumption

Palm oil is used ubiquitously as cooking oil in different Asian and West African cuisines because it is tasteless, odorless, and has a high smoke-point, which makes it safe for re-frying (Boateng et al. 2016). Due to its naturally occurring partially hydrogenated fats (Magri et al. 2015), PO results in crunchiness, palatability, and preservation properties in manufacturing (Di Genova et al. 2018), without posing the risk of cardiovascular disease (CVD) associated with industrially produced partially hydrogenated vegetable oils (Odia 2015; Magri et al. 2015). As such, PO-derivatives are commonly found in biscuits, noodles, and bakery products worldwide (Boateng et al. 2016). The health effects of widespread PO consumption remain contentious. Some studies cite adverse effects of saturated fats (Kadandale et al. 2019), while others tout protective effects on cardiovascular health, antidiabetic and anticancer properties, and reproductive health improvement (Giri and Bhatia 2020; Ibrahim et al. 2020a, b) due to PO-derived phytonutrients such as tocotrienols and carotenoids, which is converted into an important micronutrient, Vitamin A.

Phytonutrients and oxidative stability (SDG2)

Red PO (RPO) is known to possess pro-vitamin A activity (Loganathan et al. 2017) and used in vitamin A fortification programs due to its resistance to oxidation and stability (Pignitter et al. 2016). However, RPO trials for preventing Vitamin A deficiency, a key factor in preventable blindness and severe infection in low-income countries, have garnered inconsistent results, with some reporting RPO supplementation effective, and others concluding a lack of significant effects (Dong et al. 2017). Nevertheless, compared to RPO, which retains 80% of its vitamins and carotenoids, most PO consumed as cooking oil or in processed food is refined, bleached, and contains less phytonutrients.

Palm oil also contains relatively high amounts of tocotrienols, a form of vitamin E known to scavenge free radicals for prevention of pathologies (Jegede et al. 2015). Animal studies on PO tocotrienol rich fraction (TRF) suggest beneficial effects such as prevention of bone loss (Wong et al. 2018), amelioration of Alzheimer's related behavior and cognitive impairments (Durani et al. 2018), and improvement in antioxidant levels through modulation activity of antioxidant enzymes (Nor Azman et al. 2018). However, these benefits have not been convincingly observed in human trials such as those on TRF treatment in diabetes (Tan et al. 2018).

Saturated fats and contaminants (SDG3)

Adverse health impacts of PO are related to its saturated fatty acid (SFA) content, whereby the carbon chain "saturated" with hydrogen purportedly increases low-density lipoprotein (LDL) cholesterol, reduces fat oxidation (Yajima et al. 2018), and elevates risk of CVD. However, the majority of SFA in PO is palmitic acid (44%), known to be less potent in raising LDL cholesterol, unlike lauric and myristic acids, which are present in trace amounts (Magri et al. 2015; Boateng et al. 2016).

The association between PO carbon chain saturation and increased risk of CVD is subject to debate. Some claim unsaturation (at the sn-2 position) alters PO characteristics to mimic monounsaturated oils such as olive oil, instead of harmful saturated animal fats (Sin Teh et al. 2018). Others claim that the degree of saturation has a greater effect on blood lipid concentration than the positional distribution of SFAs (Sun et al. 2015). A randomized trial studying the effects of hybrid PO supplementation on human plasma lipid patterns concluded that effects on plasma lipids were comparable to extra virgin olive oil, which is typically consumed for its protective effects on cardiovascular health (Lucci et al. 2016), although notably, the study evaluated crude HPO (from *E. guineensis* and *E. oleifera*), which differs from refined PO in its content of vitamin E and carotenoids.

In animal studies including murids and fish, high-fat diets of PO and/or consumption of polar compounds from deep-frying of PO were associated with elevated levels of LDL, triglycerides (Sales et al. 2019; Larbi et al. 2018), and alkaline phosphatase-induced liver lipid accumulation (Janssens et al. 2015), changes in offspring's adipose tissue in adult life (Magri et al. 2015), and impaired glucose tolerance (Li et al. 2017). Conversely, PO supplementation in sheep feed has been shown to reduce SFA content, thus increasing mono- and polyunsaturated fatty acid content in sheep milk (Bianchi et al. 2017).

The evidence appears more equivocal in humans, especially under conditions of regular consumption. A systematic review by Ismail et al. (2018) challenged the link between PO consumption and the elevation of LDL concluding the lack of strong evidence for increased risk of CVD (Ismail et al. 2018), while an earlier systematic review and meta-analysis of clinical trials by Sun et al. (2015) concluded that PO consumption results in higher LDL cholesterol compared to vegetable oils low in saturated fat, but results in higher HDL cholesterol compared to trans-fat-containing oils in humans. These reviews are notably limited by a small number of studies and publication biases based on funding source, widespread consumption, and difficulty to single out PO from other food items (Ismail et al. 2018; Sun et al. 2015). A recent randomized controlled-feeding trial in healthy normocholesterolemic adults showed that butter raised LDL cholesterol higher than palm stearin regardless of background consumption of carbohydrate and fat (Hyde et al 2021). Thus far, the oft-cited negative effects of saturated fats from PO remains inconclusive.

Finally, processing and manufacturing issues, especially for non-branded oils known to contain less favorable SFA composition (Aung et al. 2018) and increased PO contaminants pose additional health risks. However, such risks may be mitigated with improved industry standards and regulation (Di Genova et al. 2018). Ultimately, consumption of PO, especially in a healthy balanced diet, does not appear to pose significant elevated risk for chronic diseases such as CVD, diabetes, and cancer in adult or pediatric populations (Odia 2015; Di Genova et al. 2018; Mancini et al. 2015; Marangoni et al. 2017; Bronsky et al. 2019). Reducing PO consumption by 50% is predicted to only have a relatively small impact on health (Jensen et al. 2019), unless it is part of a broader dietary and nutritional strategy to achieve significant improvements in health.

Social and economic impacts of the palm oil industry

National economic growth (SDG9, 12)

Most plantations in Malaysia are large-scale plantations with 61% of these plantations belonging to private estates, 22% governed under governmental schemes (half of which, belong to smallholders (van Leeuwen 2019), i.e., family-based plantations of less than 50 ha) and 17% owned by independent smallholders (MPOB 2017). Smallholders produce PO independently and sell their produce directly to a mill or through various governmental schemes (RSPO 2018). More than 300,000 smallholders, including farmers of indigenous tribes both in East and West Malaysia, contribute to more than 18 Mio t of annually exported PO (Hamid et al. 2013). Although, OP agriculture is commonly associated with Borneo, in 2017 Peninsular Malaysia contributed a larger fraction of Malaysia's total PO products (ca. 52%) (MPOB 2018; Shevade and Loboda 2019).

Approximately 30% of all globally produced vegetable oils is PO, accounting for two thirds of exported oils by volume (Shevade and Loboda 2019). Increasing demand from China and India stimulated the rapid growth of the PO industry, with Malaysia supplying 44% of globally exported PO (MPOB 2017; Shevade and Loboda 2019; Brandi et al. 2015). Through a series of policies, including the implementation of New Key Economic Areas for PO (Jomo and Rock 1998; Pemandu 2010), Malaysia has further fostered domestic PO refining businesses, achieving a refining capacity of 26.5 Mio t pa exceeding its annual CPO production (MPOB 2020). The PO sector also draws foreign investments to Malaysia (Mekhilef et al. 2011; Shevade and Loboda 2019) and earnings through corporate taxes (Mahat 2012). Since 2008, the industry contributed ca. MYR65.2bil (ca. USD16bil) in exports (Mekhilef et al. 2011; MPOB 2017), and by 2015, PO contributed to 4.2% of Malaysia's GDP (Shevade and Loboda 2019), and currently 37.7% of agricultural GDP (DOSM 2020).

Poverty alleviation and food security (SDG1, 8, 10)

Since the 1950s, the PO industry has been a catalyst for development (Awang Ali et al. 2011; Arif and Tengku Mohd Ariff 2001; Mahat 2012), becoming a major employer and key contributor to rural growth in Malaysia (Feintrenie et al. 2010; Rist et al. 2010; Lee et al. 2014; Castiblanco et al. 2015; Gatto et al. 2017; Choiruzzad 2019; Arif and Tengku Mohd Ariff 2001). Since 1956, progressive land expansion schemes led by the Federal Land Development Agency (FELDA) aimed to develop plantation land for the landless and rural poor Malays (Teoh 2002) and increased smallholder income from traditional crops (Awang Ali et al. 2011; Mahat 2012). With ca. 85 k ha of developed land and resettling of ca. 110 k families (Ahmad Tarmizi 2008), FELDA has contributed to poverty alleviation amongst settlers with the reported average monthly household income of FELDA smallholders increased from MYR1338 in 2006 to MYR3000 in 2010, exceeding the national poverty limit of MYR720 per month (Ahmad Tarmizi 2008).

The PO industry employs approximately 2.3 million people in Malaysia (Mahat 2012), contributing to Malaysia's low unemployment rate of ca. 3.4%, which only recently increased to 4.6% due to the COVID-19 pandemic (DOSM 2021). Insufficient local labor supply has also led to an influx of one million foreign workers from neighboring developing countries who are mainly employed in plantations and mills (Basiron 2011), including smallholder plantations (Awang Ali et al. 2011) but recruitment activities in the PO industry have stalled since the pandemic. The plantation sector employs more than 70% foreign workers and the ongoing national and international travel restrictions imposed to curb the impacts of the pandemic have caused labor shortages by 500,000 workers, resulting in a 3.8% decrease in PO production between 2019 and 2020. The ongoing COVID-19 pandemic has also led to a decline of PO exports from 18.5 Mio Mt in 2019 to 17.4 Mio Mt in 2020 (MPOC 2020).

In rural areas with limited job opportunities, government incentives enabled farmers to develop their plantations (Asmit and Koesrindartoto 2018) while simultaneously increasing employment opportunities. The labor-intensive plantation sector only has low level mechanization; thus, workers are required for fruit harvesting, collection, and other fieldworks (Ismail 2013). Growing OP is also a lucrative and popular side crop for farmers of other lower-yielding but government-incentivized agricultural crops such as paddy (Alam et al. 2010). Small growers often practice mixed farming by raising livestock and cultivating fruits and vegetables at the OP plantations, enhancing income opportunities (Ashraf et al. 2018). Consequently, OP cultivation along with mixed agricultural activities are associated with improved standard of living throughout the country, narrowing the income gap between rural and urban workforce (Mahat 2012; Hamid et al. 2013; Man et al. 2013). However, smallholders in less accessible areas suffer land shortage and encroachment from nearby estates, rendering them more vulnerable to fluctuations in crude PO prices (Azhar et al. 2020).

Poverty and food security are inextricably linked, and the PO industry generally contributes to both increased employment and food security in Malaysia and globally, as PO remains the world's most affordable edible vegetable oil, and a staple in low-middle income countries across Asia, Africa, and the Middle East (Boateng et al. 2016). Improved income arising from agricultural activities such as rubber and OP cultivation, in combination with traditional hunting and gathering activities, appears to be associated with lower risk of malnutrition among certain indigenous tribes, such as the Jah Hut in Pahang (Law et al. 2020). However, OP plantation expansion has negative impact on rural and indigenous food security when land rights of these rural communities are violated (Nesadurai 2013).

Social conflicts and adverse impact on indigenous peoples (SDG8)

Conflicts are common between indigenous peoples in Malaysia and large companies who were granted development permits in forest reserves, while low wages and/or human rights violations of foreign plantation workers continue to tarnish the reputation of the industry (Wan Daud et al. 2020). Oil palm expansion may also contribute to rising inequality among farmers or between communities (Gatto et al. 2017; Cramb and McCarthy 2016), especially when farmers are forced to sell their land, consequently losing means for their own agricultural production (Bou Dib et al. 2018; McCarthy 2010).

In Sabah and Sarawak, most plantations are on steep hills that were converted from agricultural land with slash-and-burn techniques (Wicke 2011). Traditionally, burning of plant material in old plantations to get rid of unwanted plant waste can enhance nutrient availability in depleted soils (Knicker 2007), but this technique has led to dramatic haze problems throughout Southeast Asia (Padfield et al. 2016), and directly reduced the life quality of farmers living in affected areas (Obidzinski et al. 2012). Many communities that depend on ecosystem services such as clean rivers, natural forest products and/or small-scale agricultural activities for income are highly affected by land conversion, as they lose access to these resources (Martin 2017; Awang Ali et al. 2011; Mahat 2012). Furthermore, chemical fertilizers and pesticides used in large-scale plantations may pollute freshwater resources that are essential to indigenous and rural communities (Obidzinski et al. 2012; Bou Dib et al. 2018; Dudgeon et al. 2006).

The emphasis for commodity crops such as OP and rubber and the rapid expansion of plantations and intensive logging may have indirectly contributed toward poverty and heightened vulnerability of some indigenous peoples in Malaysia (Kari et al. 2016; Wan Daud et al. 2020). Barriers in technology and knowledge transfer to indigenous farmers and small growers renders them less empowered to use best practices that can improve yield while minimizing practices with adverse impacts, such as slash and burn for clearing of old OP trees (Rochmyaningsih 2015). Indigenous small growers also suffer more threats from wild animals, given that they tend to cultivate farms close to forests (Law et al. 2018). Such threats to safety often contribute to agricultural failure, and consequent food insecurity among indigenous people.

Impact of oil palm cultivation on the environment and biodiversity

Land use policies in Malaysia are regulated by the state governments. Half of all plantations are planted on state forest land that was previously used for rubber or other uses (Hansen et al. 2014; Padfield et al. 2019). From 2010 to 2018, OP plantations reportedly increased by 5.06 Mha at a growth rate of 83.5%, with growth rates for East and West Malaysia at 109.5% and 62.1%, respectively (Li et al. 2020). The deforestation for new OP plantations between 2001 and 2017 reached 5.98 Mha accounting for 68.2% of the total amount of deforestation in Malaysia for that period (Li et al. 2020). While west Malaysian plantations mostly expanded on former rubber plantations (Barlow 1997), in Sabah and Sarawak, plantation expansion has driven deforestation with 4.2 Mha of old growth forest cleared between 1973 and 2015 (Gaveau et al. 2016). Compared to Indonesia, Malaysia had a more rapid conversion rate of these cleared lands of ca. 60% within a 5-year time frame (Gaveau et al. 2016).

Specifically for peatlands, plantation area reportedly increased by ca. 200 kha between 2003 and 2008 (Edwards et al. 2010), amounting to one-third of the total new plantations, with the majority occurring in Sarawak (Edwards et al. 2010). However, Gunarso et al. (2013) reported a lower estimate of 13% of OP planted on peatland in 2010. Records from a 250 m spatial resolution map showed that more than 800 kha of Malaysian tropical peat swamp have been converted to OP plantations (Koh et al. 2011). Specifically, Sarawak and Sabah had 49.5% and 34.6% of peatlands covered by OP, respectively, in 2015 (Miettinen et al. 2017). However, since 2015, over 90% of internationally traded PO followed producer commitments for the ‘no deforestation and no peat’ policy (Austin et al. 2015; Butler 2015). More recently, Wan Mohd Jaafar et al. (2020) reported declined conversion of peatland to plantation by 20.5% and 19.1% in Sarawak and Sabah, respectively.

Land use change for agriculture is associated with adverse impacts on the environment through increased greenhouse gas (GHG) emissions, soil erosion, and microclimate and regional climate changes, i.e., change in temperature and precipitation, and increased risk of flooding (Gaveau et al. 2014; Uning et al. 2020; Wolf 1996).

Emissions, soil, and climate (SDG6, 13).

Malaysia is the fourth highest carbon emitter from forest degradation with over 140 Mio t CO_2 pa after Indonesia, Brazil and India (Harris et al. 2012; Pearson et al. 2017; Begum et al. 2020). The conversion of forest into OP plantations reduced carbon stocks by over 50% and increased GHG emissions by four times, compared to land converted from old rubber plantations (Kusin et al. 2017). Plantations on peat in Malaysia emit GHG ranging from 12.4 up to 76.6 t CO_2-eq ha^{-1} pa (Hashim et al. 2018), with highest emissions recorded in Selangor (65 t C ha^{-1}) in 2006, and the lowest in Sarawak (7 t C ha^{-1}) (Matysek et al. 2018; Melling et al. 2005, 2008, 2013). Cooper et al. (2020) suggest that conversion of peat swamp forest in Malaysia contributes between 16.6 and 27.9% (95% CI) of combined total national GHG emissions. CO_2 release from drained peatland is higher than from mineral soils as peat stocks hold higher quantities of carbon (Choo et al. 2011; Hashim et al. 2018; Page et al. 2011). This loss of stocked carbon increases during the dry season, facilitated by longer and more intense dry seasons associated with current global climate emergency (Matysek et al. 2018). Additionally, plantations on peatlands lead to degradation and fires (Page and Hooijer 2016; Page et al 2009), which are associated with significant air pollution and threats to human health in the region (Uda et al. 2019; Crippa et al. 2016).

While OP plantations and associated cultivation practices emit up to two times more CO_2 than other crops, they also absorb CO_2 and produce around 18 t O_2 ha^{-1} pa (Uning et al. 2020). The emission difference between different croplands depends on the type of soil and amount of carbon stocks, drainage and fertilizer use, and methane use at the mills (Hashim et al. 2018). However, CO_2 uptake above OP canopy of 82 t C ha^{-1} pa was recorded in Sabah and this is reportedly higher than from intact forests (32 t C ha^{-1} pa) (Fowler et al. 2011; Sharvini et al. 2020), suggesting potential carbon neutrality of OP cultivated lands (Kusin et al. 2017).

Plantations’ nitrous oxide (N_2O) emissions are lower than those of primary forests as forest soils are a better source of N_2O than plantations (Yashiro et al. 2007). Newly established OP plantations show slightly higher N_2O emissions than older plantations due to the use of fertilizers and other environmental factors (Melling et al. 2007; Yashiro et al. 2008), but overall N_2O emission levels seem similar in OP plantations of different ages (Kusin et al. 2017). Consistent with other studies (Holzinger et al. 2002), emissions of isoprene (C_5H_8), CO_2, and surface ozone (O_3) from OP plantations in Pahang were temperature-dependent, with lower emission during cooler temperatures at night (Uning et al. 2020). Increased NO_x emissions over plantations are caused by fertilizer and PO plant combustion and vehicle exhausts (Uning et al. 2020).

Evapotranspiration processes, but not the amount of precipitation, are impacted by land conversion from forests into OP plantations (Amin et al. 2016). Oil palms planted on steep terrain cause negative hydrological impacts such as increased flooding risk, modification of river ecology, and sedimentation (Nainar et al. 2018; Saadatkhah et al. 2016). Soil mineralization rates are similar between OP plantations and forests in Sabah (Hamilton et al. 2016) with approximately 90% reduction of denitrification and anaerobic ammonium oxidation disrupting nitrogen gas (N_2) production. Consequently, high nitrate concentration occurs in ground water of OP plantations, due to the application of N-fertilizers (Sheikhy et al. 2018).

Changes in microclimate directly impact plant growth and soil nutrient processes, with the temperature inside plantations increased by 6.5 °C compared to primary forest in Sabah (Hardwick et al. 2015). The change in regional climate manifests through increased rainfall, temperature, radiation, atmospheric pressure, cloud cover, and a decrease in evaporation, relative humidity, sunshine hours, and wind speed due to intensive land use change in the Kelantan River Basin between 1984 and 2014, which follows trends found across Malaysia (Nurhidayu and Hakeem 2017).

Biodiversity (SDG14, 15)

There is still poor understanding of how species respond to anthropogenic disturbance in tropical primary forests (Silmi et al. 2013; Fitzherbert et al. 2008) but biodiversity decline of different species of arthropods, fish, amphibians, birds, and mammals in Malaysia due to the expansion of plantations into natural habitats is well documented (Vijay et al. 2016; Brandon-Mong et al. 2018). Some indicator species may predict changes in diversity and geographical distinctness in relation to habitat disturbance. For example, fruit-eating butterfly abundance in Sabah was lowest in OP plantations compared to primary and logged-over forest (Koh and Wilcove 2008), and species richness was lower in areas converted from primary or secondary forest to OP plantations compared to conversion from existing rubber to OP plantations (Koh and Wilcove 2008; Hamer et al. 2003). Oil palm plantations in Sabah showed lower species richness of ants compared to riparian reserves and logged forests (Fayle et al. 2010; Gray et al. 2015). Most ant species in plantations were non-forest species (Brühl and Eltz 2010), suggesting that conversion of forest into plantations results in replacement of native forest ant species with more dominant invasive species. However, when assessing the ratio between regional and local species at a large spatial scale, more common and abundant species of ants were found in OP plantations than forests (Wang and Foster 2015).

Species richness of freshwater fishes was lower in rivers near OP plantations in Bintulu, Sarawak (Kano et al. 2020), and species diversity of amphibians (i.e. order Anura) was lower at OP plantations in Selangor compared to grassland, coconut plantation, and primary forest (Faruk et al. 2013). Similarly, anuran species richness was higher in primary and secondary forest habitats compared with OP plantations in Sabah (Aguilar-León 2020).

Less than 50 species of forest birds were recorded in OP plantations in Sabah demonstrating the lowest diversity compared with primary forest, logged forest and rubber plantation (Koh and Wilcove 2008). The diversity and density of insectivorous and frugivorous bird species were also lowest in OP plantations compared to secondary forests and paddy fields in Kerian River Basin, Peninsular Malaysia, due to lower tree density and basal areas and less fruit availability in plantations (Azman et al. 2011).

A substantial decline of terrestrial mammal abundance in OP plantations compared to nearby forests was reported from Sabah (Wearn et al. 2017; Yue et al. 2015). Although plantations offer food resources to mammals like the Malayan sun bear (Guharajan et al. 2018), camera trap studies recorded their presence in forest patches rather than highly degraded areas such as plantations (Abidin et al. 2018). Sunda clouded leopards appear intolerant to deforestation and forest fragmentation in the Lower Kinabatangan and Kabili-Sepilok areas that are composed of small forest patches embedded with OP plantations (Hearn et al. 2018, 2019) highlighting these as priority areas requiring protection for threatened felid species (Hearn et al. 2016a; b; c).

Conversely, OP plantations hosted the highest number of carnivorous birds including striated, Chinese and Javan pond heron at Kerian River Basin, Perak due to the high availability of prey such as shrews, snakes, and rats (Azman et al. 2011). Plantations may even bring positive effects for selected species, such as the black-shouldered kite, as they provide good vantage positions, shelter from predators and a suitable physical environment for such species (Ramli and Fauzi 2018).

Human–wildlife conflict (SDG15)

Human–wildlife conflict is a main driver of species loss across the globe (Meijaard et al. 2018) usually due to illegal hunting caused by economic constraints, demand for exotic pets and products, road kills, and culling of crop pests (Azhar et al. 2013; Liu et al. 2011). Wildlife poaching is facilitated by habitat conversion to OP plantations and other agricultural crops (Azhar et al. 2013). Terrestrial animals that are highly dependent on forest, such as elephants, tend to forage in the plantations, which is perceived as raiding due to their destructive feeding habits (Guharajan et al. 2018; Cazzolla Gatti and Velichevskaya 2020). Human–elephant conflicts in plantations in the lower Kinabatangan in Sabah are driven by incidental poaching or revenge killings of elephants by plantation workers, although elephants usually actively seek to avoid humans (Evans et al. 2020). While managing elephant populations surrounding plantations via translocation to other areas appears to be an option, studies suggest that this practice is harmful to their populations. A population viability assessment of Asian elephants in the Endau Rompin landscape showed that even translocating only a few individuals poses risks on the population, suggesting the need for an in-situ management plan at OP plantations to curb human–elephant conflicts (Azhar et al. 2013; Asimopoulos 2016; Saaban et al. 2011).

Efforts to enhance benefits and mitigate adverse impacts

As summarized above, the impact of widespread PO production and consumption on different aspects of SDGs are undeniable (Table 1). However, to effectively expand on positive effects of PO while addressing adverse effects, there is a need to holistically evaluate different mitigation strategies and identify co-benefits and trade-offs on different SDGs. We summarize potential co-benefits and trade-offs of specific mitigation strategies in Fig. 1, proposed based on the evidence discussed below.

Replacing palm oil with a different oil (SDG 1–3, 6–10, 12–15)

The negative perception of PO usually relates to deforestation and replacement of more diverse agricultural or agroforestry systems with these monocultures (Meijaard and Sheil 2019). However, debates about PO by supporters and opponents are often highly polarized. Calls for boycotting PO do not consider the fact that (1) OP is the highest yielding available oil crop requiring eight times less land and producing up to 20 times more oil compared to soybean, canola and sunflower (Low 2019; Woittiez et al. 2017); (2) OP crops may alleviate poverty among rural growers who may have little opportunity for other income-generation, especially in Malaysia (Sheil et al. 2009; Pirker et al. 2016); (3) economic reliance on PO in the region is widespread (Shevade and Loboda 2019); and (4) cultivation practices are heterogeneous with varying policies and enforcement practices in producer countries affecting impact (Meijaard et al. 2018). On the other hand, OP supporters often do not weigh in the losses of biodiversity and related ecosystem services but instead argue from nationalistic and socioeconomic perspectives (Liu et al. 2020).

Removing or replacing PO globally would likely adversely impact food security to producer and consumer countries (Gro Intelligence 2016) as restrictions would not only affect the demand, consequently reducing livelihood of producers, but also impact the supply of this edible oil, thus, leading to higher prices of cooking oil and consumer goods that would affect other sectors as well. A comparison of five major vegetable oil crops by Beyer et al. (2020) concluded that better management of future growing areas will be more effective at reducing environmental impacts of global vegetable oil production rather than oil crop substitution. Despite OP having larger impact on range-restricted species, OP was estimated to pose the lowest carbon and species richness loss per-ton-oil (Beyer et al. 2020). Thus, removing or replacing PO may lead to higher biodiversity losses in the future as more land needs to be converted to cultivate lower yielding oil crops leading to further habitat destruction (Meijaard et al. 2018).

Policies and regulations (SDG1,6–10,12–15)

Sustainable certification and 'no deforestation, no peat, no exploitation' (NDPE) policies

Generally, GHG emissions in Malaysia can be reduced by 4.1 t CO_2-eq ha^{-1} pa simply by banning the establishment of new OP plantations on peat soil (Hashim et al. 2018). Additionally, the environmental sustainability of OP can be improved by stopping burning practices, reducing the use of peatland and swamp areas, and replacing fossil fuels by biofuel for plantation activities (Uning et al. 2020). Hence, to fulfil the growing global demand for PO while achieving conservation goals, voluntary certification under the international Roundtable Of Sustainable Palm Oil (RSPO) aims to ensure sustainability through a set of standards, accreditation, and process requirements (RSPO 2017; Abazue et al. 2015), encompassing optimization of productivity and efficiency while adhering to transparency, ethical, and legal principles, respecting communities, supporting smallholders, and protecting workers, while conserving the larger ecosystem.

While Malaysia is already a signatory of the RSPO network (Abazue et al. 2015), the Malaysian Sustainable Palm Oil (MSPO) certification scheme was established in 2015 to improve the PO governance and branding of Malaysian PO through nationwide sustainability initiatives, and transparency throughout the value chain (Pacheco et al. 2018).

Table 1 Summary of impact, mitigation strategies and recommendations related to palm oil production in Malaysia aligned with the SDGs

	Environment	Biodiversity	Health	Socioeconomic
Associated SDGs and their keywords	Deforestation, plantation emissions and waste management impact clean water (SDG6), and climate action (SDG13) SDG6: clean water, ecosystem protection, floods, pollution, rivers SDG13: climate resilience, CO_2 capture, ecosystems, emissions, greenhouse gas emissions, pollution, temperature	Deforestation and human-wildlife conflict compromise on diversity and abundance of native aquatic (SDG14) and terrestrial (SDG15) species SDG14: marine pollution, water resources and policy SDG15: land loss, land use and sustainability, poaching, protected species, species, terrestrial ecosystems, threatened species	Consumption of PO as a cheap, abundant, and phytonutrient-rich oil allows for alleviation of micronutrient deficiencies (SDG2) but may have adverse cardiovascular impact (SDG3) SDG2: food, improved nutrition, nutritional needs SDG3: diseases, health	Diverse impact on human quality of life (SDG10), livelihood (SDG1, SDG8), and industrial (SDG9), alternative energy (SDG7), and national growth and development (SDG12) SDG1: poverty, poverty eradication, resources SDG7: renewable energy SDG8: forced labor, GDP growth, global trade, innovation, job creation, migrant workers, modern slavery, poverty eradication, social policies, sustainable economic growth SDG9: economic development, environmentally sound technologies, industrial diversification, Value chains and markets SDG12: natural resources, reduce waste generation, resource efficiency
Benefits	N_2O emissions are lower than in primary forests (Yashiro et al. 2007) OP plantations absorb CO_2 and produce around 18 t O ha^{-1} pa^{-1} (Uning et al. 2020). CO_2 uptake above OP canopy on average higher than from intact forests (Fowler et al. 2011; Sharvini et al. 2020)		High amounts of phytonutrients (e.g., tocotrienols) in red PO flags potential role in economical supplement and fortification programs (Jegede et al. 2015; Pignitter et al. 2016; Loganathan et al. 2017; Dong et al. 2017; Selby-Pham et al. 2020) Oxidative stability makes PO a safer alternative for long-term storage, repeated use, and high heat cooking (Boateng et al. 2016; Magri et al. 2015)	As a high-yield industry, PO is a key national economic resource, attracting foreign direct investments, employing locals and foreign workers, stimulating biofuel industry, alleviating rural poverty, and contributing to domestic and regional food security (Shevade and Loboda 2019; DOSM 2020; MPOB 2018)

Table 1 (continued)

	Environment	Biodiversity	Health	Socioeconomic
Adverse effects	Conversion of forest into OP plantations were associated with: Increased GHG emissions, reduced carbon stocks (Kusin et al. 2017; Choo et al. 2011; Hashim et al. 2018; Page et al. 2011; Matysek et al. 2018); highly reduced denitrification and enhanced N emissions due to fertilizers, plant combustion and vehicle exhausts (Hamilton et al. 2016; Drewer et al. 2020; Uning et al. 2020); increased flooding risk and sedimentation (Nainar et al. 2018; Saadatkhah et al. 2016); and microclimate and climate changes (Hardwick et al. 2015; Nurhidayu and Hakeem 2017) Peat swamp forests are much more prone to fire than any other forest type (Page and Hooijer 2016; Page et al. 2009) and plantation peatland fire-led haze increases air pollution–related premature mortality at 648 cases per year (26 mortality cases per 100,000 population) due to chronic respiratory and cardiovascular diseases and lung cancer (Uda et al. 2019; Crippa et al. 2016)	Expansion of OP plantations into natural wildlife habitats threatens biodiversity and can result in reduced species abundance, local extinctions, or invasive species (Koh and Wilcove 2008; Brühl and Eltz 2010; Azman et al. 2011; Vijay et al. 2016) Forest fragmentation leads to human wildlife conflicts, poaching, and illegal wildlife trade (Liu et al. 2011; Azhar et al. 2013; Evans et al. 2020)	Saturated fat content of PO increases risk of CVD when consumed excessively (Yajima et al. 2018; Ismail et al. 2018; Sun et al. 2015) Risk of contaminants higher, especially in non-branded oils due to poorly regulated manufacturing processes (Aung et al. 2018; Di Genova et al. 2018)	Social conflicts arising from some practices in the PO industry were linked to "modern slavery" of migrant workers (withholding salaries and passports), land right issues affecting rural and indigenous communities (Wan Daud et al. 2020), deforestation and pollution, which threaten quality of life of local communities Differences in knowledge, technological adoption, and land ownership widens the gap between large companies and small growers and contributes to rising inequality among farmers and between communities (Rochmyaningsih 2015)

Table 1 (continued)

	Environment	Biodiversity	Health	Socioeconomic
Mitigation opportunities	Riparian buffer establishment to mitigate emissions and microclimate changes (Chellaiah and Yule 2018; Luke et al. 2017; Mitchell et al. 2018) Waste conversion of POME residues (Rupani et al. 2010) into biofertilizers (Truckell et al. 2019), PO mills waste into biobutanol and other (Rubinsin et al. 2020; Szulczyk and Cheema 2020). Use of OP shell in cement as an aggregate agent (Hamada et al. 2020) Intercropping to reduce soil erosion, spread of plant diseases and reliance on herbicides, while allowing smallholders to generate supplementary income (Ahmed et al. 2001; Hanafi et al. 2009; Ibrahim et al. 2020a, b; van Leeuwen 2019; Woittiez et al. 2017; Samedani et al. 2015) Use of biological pest control agents to decrease pesticide use and enhance biodiversity in plantations (Salim et al. 2014; Holzner et al. 2019)	Adaptation of some animal species to OP plantations creates opportunities for in situ conservation as opposed to species translocation (Azman et al. 2011) Wildlife corridors & habitat reconnection/reforestation may reduce human-wildlife conflicts and re-establish genetic flow across fragmented forest patches (Faruk et al. 2013; Bernard et al. 2014; Holzner et al. 2019) Education opportunities for habitat protection and enforcement against illegal encroachment, poaching, and wildlife trade (Meijaard et al. 2018) Certification and international agreements such as RSPO, MSPO, Aichi Targets and International Biology Convention may facilitate engagement across multi-stakeholders and stewards (RSPO 2017; Abazue et al. 2015; CBD 2011)	Encouraging moderation and overall healthy diet, instead of focusing only on PO consumption, is more prudent and likely to have a more significant impact on health outcomes (Odia 2015; Di Genova et al. 2018; Mancini et al. 2015; Marangoni et al. 2017; Jensen et al. 2019; Bronsky et al. 2019)	Effective implementation of sustainability certification may ensure protection of worker welfare and level the playing field between small growers and large-scale plantation companies through promotion of technological transfer and best practices (Nesadurai 2013) Addressing issues of inequity and fluctuating prices through governance (reducing reliance on middleman/mills) and certification promote best practices for small growers (Kumaran 2019)
Challenges	Difficulty in harmonizing different and/or competing priorities of stakeholders and jurisdictions of various stewards related to different aspects of OP plantation establishment and management Role of regulation and policies to address transboundary environmental issues (e.g., haze)	Limited funding/lack of political will Extinction cascades/accelerated species loss by multiple factors and climate change	Available data in humans remain inconsistent and equivocal, in part due to widespread presence of PO, and difficulty to tease out independent impact of PO (Sun et al. 2015; Ismail et al. 2018) Seeming publication bias due to source of funding (i.e., industry vs. independent studies) (Sun et al. 2015)	Ensuring transparency of sustainability certification, complex land laws, limited awareness of rights and access to resources for the most vulnerable stakeholders in the PO industry (Nesadurai 2013; Kumaran 2019)

Table 1 (continued)

	Environment	Biodiversity	Health	Socioeconomic
Knowledge gaps and key questions	Gaps in important information at many levels, with available data often limited to specific questions that do not address ecosystem function holistically (Gaveau et al. 2016) Lack of (international) standard framework for conducting LUC assessments and long-term (predictive) modelling of habitat conversion and its impacts on the environment and climate	Literature is widely limited to issues in Indonesia, and most discussions revolve around OP as the main cause of deforestation, but few studies highlight other agricultural activities (e.g., Meijaard et al. 2020) as driver of biodiversity loss or propose feasible mitigation efforts, especially applicable large-scale diversification schemes of existing plantations	Gaps in knowledge related to what is a moderate and safe amount of long-term PO consumption in different groups of people, differences in health impact depending on PO use in diet (cooking oil vs. ingredient) Additionally, the population level health impact of consuming PO, as regular part of diet compared to other oils remains unclear	Not clear how much sustainable certification is actually improving worker welfare, small grower productivity and income; issue with data availability Understanding of main benefits, concerns, and challenges of small growers and vulnerable communities around PO remains limited
Possible recommendations	Developing a standard framework for assessing impact of LUC (especially of peat lands) and identifying feasible management practices Improving communication between stakeholders and awareness on sustainable practices More targeted and comprehensive environmental and bioeconomic impact studies on sustainable vs. conventional PO production to assess the benefits of certification for the environment and local economy, especially for smallholders	Adopt and facilitate national policies on establishing and managing wildlife corridors, habitat protection and diversification of monocultural landscapes Increase funding (national budget) strategies that protect wildlife, habitats and mitigate human-wildlife conflicts Increase education and awareness on the importance of biodiversity and nature conservation in the public and stakeholders of the PO industry	Conduct independently funded multi-site, long-term, community or randomized trials that compare impact of PO vs. other oils as part of a larger diet in real-world setting Broader education on importance of overall balanced and nutritious diet based on standard recommendations, as opposed to overemphasis on single ingredient campaigns	Increased engagement and research to address gaps in equity as well as improving regulations to ensure vulnerable communities are protected

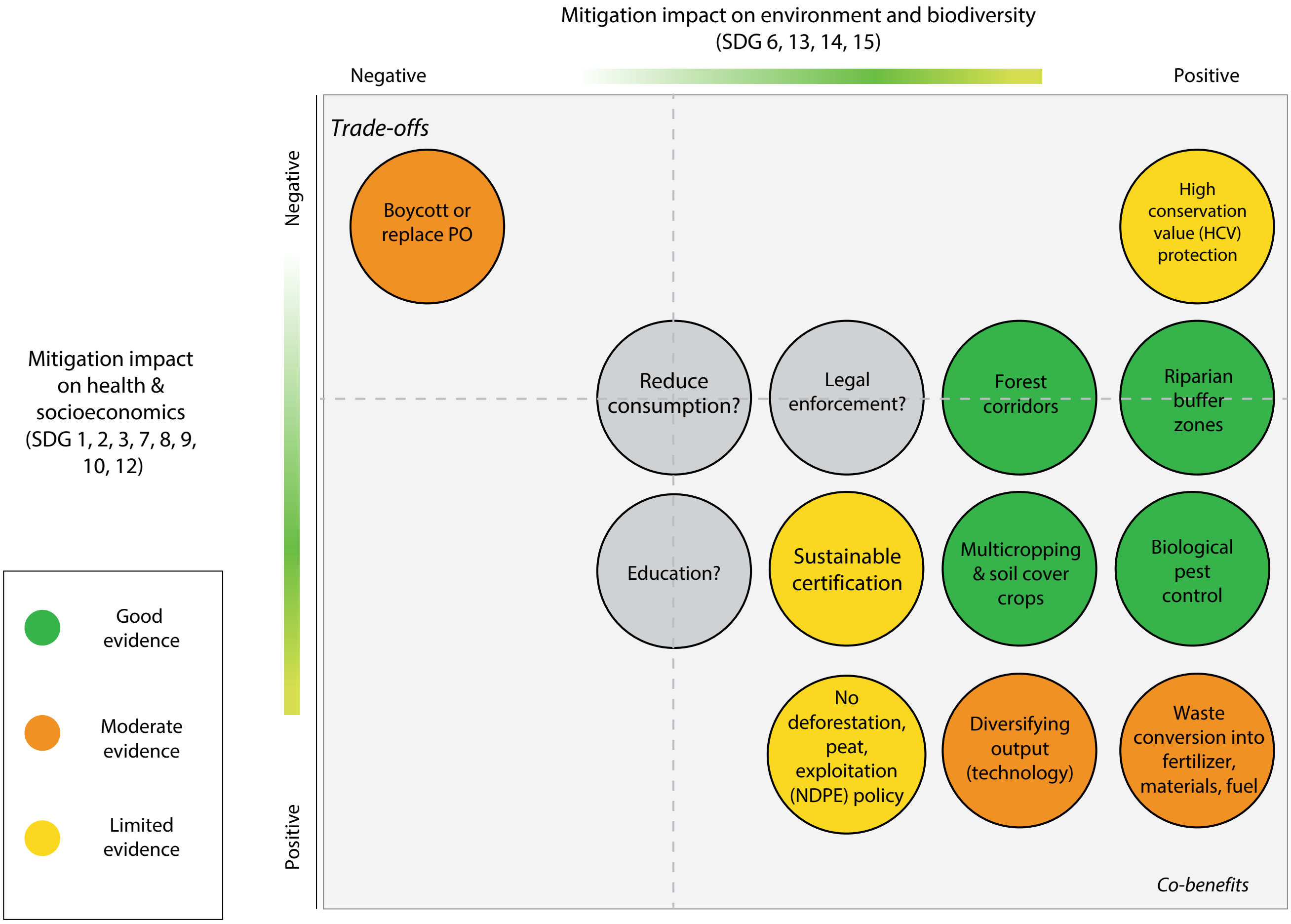

Fig. 1 Proposed interaction plot of mitigation strategies and their impact on health and socioeconomics (*y* axis) and environment and biodiversity (*x* axis) SDGs. The plot suggests that several strategies may have co-benefits, and fewer strategies are either conflicting or trade-offs that detract from efforts to achieve SDGs as a whole. Co-benefit (bottom right): positive for both; one-sided benefit (bottom left or top right): positive for either; or trade-off (top left): negative for both. Level of evidence indicated by color, i.e., green: good evidence; orange: moderate evidence; and yellow: limited evidence. Grey circles indicate potentially important elements that were unable to be directly addressed in the review

Overseen by the Malaysian Palm Oil Board (MPOB) and specifically aimed at supporting small and mid-range PO producers who cannot afford RSPO certification, the MSPO scheme has been made mandatory for OP plantations, independent smallholdings, and PO processing facilities since December 2019 (Kumaran 2019). Similar to the sustainability agenda of the RSPO that demands NDPE policies and 'no slash-and-burn practices' for certified plantations (Padfield et al. 2016), MSPO comprises seven governing principles, with 'Principle 5: Environment, natural resources, biodiversity and ecosystem services' setting the standards for mitigating impacts of OP agriculture on the biosphere.

Approximately 30% of the OP cultivated area globally is covered under voluntary or mandatory certification schemes (Kumaran 2019; RSPO 2017), and certain areas appear to be governed under multiple certification schemes (Barthel et al. 2018). Although, RSPO and MSPO ban establishment of large plantations (> 100 ha) on peatlands, this has not been enforced on the ground and slash-and-burn practices reportedly still exist (Carlson et al. 2018). Despite certification, some areas have sustained deforestation rates with major loss of tree cover and forest fires reported, and in Malaysia, the largest certified plantations have less than 1% of residual forest on their estates (Carlson et al. 2018). These reports highlight the need for routine monitoring of forest cover loss in certified plantations and penalties for members who do not comply (Carlson et al. 2018), to ensure the credibility of such certification schemes.

Although debates on the effectiveness of certification systems to mitigate forest loss and fire remain (Carlson et al. 2018), RSPO certification may reduce illegal deforestation outside of certified supply bases and act as a crucial tool to address negative impacts of PO (Heilmayr et al. 2020). However, more information is needed to determine the effect of certification on OP producers in broader areas, specifically ecological feedbacks and market forces that may improve the effect of certification. Edwards et al. (2010) proposed that funds obtained from certification of existing plantations be channeled into efforts such as biobanking and land sparing schemes that protect wildlife and forest land inside and outside of plantations. Ultimately, strict implementation of guidelines for best practices by governments and regulatory bodies, commitments to zero deforestation from all producer countries, open access of available datasets on global crop production, distribution, coverage, land cover change, and forest loss, tracking of milestones of international agreements, and legal enforcement of best practices embedded in national laws are needed to improve sustainability of PO production practices (Edwards et al. 2011).

Plantation expansion cap and high-conservation value policies

Malaysia recently committed to capping area expansion for OP plantations at 6.5 Mio ha until 2023 (Tan 2019), aiming instead to boost yield (De Pinto et al. 2017) and diversification to reduce dependency on land expansion (MPOB 2018). Besides curbing plantation expansion, high conservation value (HCV) approaches exist (often under certification schemes) to protect biological, ecological, social, or cultural values of outstanding significance, amounting to six HCV categories (HCV Resource Network 2021). HCV areas are identified at a plantation, farm or management unit level through an HCV assessment (Senior et al. 2015; Fleiss et al. 2020), which are then managed and monitored by land developers and other stakeholders. Assessment reports are publicly available and details HCVs present in specific areas as well as the evaluation results (HCV Resource Network 2021). For example, HCV detailed assessment reports for government plantations in Terengganu (Crawshaw 2019) and Sarawak (Sőzer 2016) describe at length the state of identified HCVs, such as specific mapped areas and the vegetation and wildlife species present, threats to different HCVs, and recommendations to manage the threats. While HCVs have yet to show concrete mitigatory impact in Malaysia, they may prove to be effective regulatory tools in the long term if there is commitment for transparent implementation and monitoring. Currently, although HCV assessments have been found to be beneficial, lack of monitoring indicators for plantations managers was identified as a barrier to efficient HCV implementation (Pillai 2020). Encouragingly, the Malaysian Palm Oil Green Conservation Fund (MPOGC) was incorporated on 19 February 2020 to support conservation projects such as the planting of 1 million forest trees in Lahad Datu, Sabah and the Orangutan Population Census and Pygmy Elephants program, a collaboration between the Malaysian Palm Oil Council (MPOC) and the Sabah State Government (Azian et al. 2020), which leverages on data highlighting the need to support these species in fragmented areas (Simon et al. 2019).

Biodiversity-friendly plantation management (SDG6, 13–15)

Forest corridors and riparian buffer zones

Best practice policies and the aim to achieve “biodiversity-friendly” conditions in plantations were among the top questions identified for biodiversity research (Coleman et al. 2019). Creating wildlife corridors by reserving forest patches in and around OP plantations, reforestation of underproductive OP plantation areas, and creation of forest buffer zones along rivers are necessary mitigation measures to enhance fitness of transient and vulnerable wildlife populations in OP landscapes (Wilting et al. 2012; Faruk et al. 2013; Bernard et al. 2014; Hearn et al. 2016a, b, c, 2018; Yamada et al. 2016; Holzner et al. 2019).

Riparian forests near water sources are recognized as important buffers to reduce water contamination from plantations and stabilize riverbanks (Gray et al. 2015; Luke et al. 2019), and to improve hydrology, biodiversity, ecosystem services and landscape connectivity (Marczak et al. 2010). Riparian reserve soils in Sabah release constant low rates of N_2O and NO independently of soil moisture under controlled conditions in contrast to OP plantations and logged forests (Drewer et al. 2020). Streams adjacent to OP plantations with a riparian buffer in Sabah were more shaded with cooler temperature and higher quantity of leaf litter (Chellaiah and Yule 2018; Luke et al. 2017). Carbon stocks in buffers surrounded by OP plantations were similar to intact riparian areas but were highly variable depending on the survey area (Mitchell et al. 2018; Fleiss et al. 2020). Anuran diversity in plantations was enhanced by proper biodiversity management strategies such as maintenance of stream complexity, riparian buffers, and reduced use of mechanical dredging (Faruk et al. 2013), whereby the presence of buffers or patches of forest does not impact OP yield (Edwards et al. 2014).

Additionally, Bornean orangutans show behavioral flexibility and nesting behavior in certified plantation areas with available forest patches (Ancrenaz et al. 2018; Santika et al. 2019). Orangutans of all sex-age groups were found in OP plantations in Kinabatangan as these plantations constitute a source of food and shelter to build nests, as well as travel corridors (Ancrenaz et al. 2015; Sherman et al. 2020). To ensure survival of orangutans, protection of certain tree and canopy attributes of remaining forest patches is crucial due to their large size, far travel distance, and other minimal ecological requirements of these great apes (Davies et al.

2017). Conversely, tree height and canopy cover showed no significant effects for making plantations more hospitable for other (small terrestrial) mammals, but additional land sparing strategies were suggested to tackle space and resource constraints (Yue et al. 2015). Bearded pigs along the Lower Wildlife Kinabatangan Sanctuary, Sabah regularly use OP plantations as habitat although secondary forest fragments are used for a wider range of behaviors such as nesting and wallowing (Love et al. 2018). Hence, although many species can adapt to plantations, forest patches are still important for them to flourish.

Multi-/inter-cropping and soil cover crops

Intercropping of OP plantations with other crops is practiced widely in Malaysia (Corley and Tinker 2016; van Leeuwen 2019), often by smallholders to generate income in the first years of planting before the palm trees produce fruits (Ahmed et al. 2001; Hanafi et al. 2009), and if performed on peat soil, intercropping has positive effects such as protecting the soil from erosion and improving its quality. Intercropping reduces harmful pathogens, such as fungi (Woittiez et al. 2017) that spread from old to new plantations (van Leeuwen 2019) but more studies are needed to confirm the benefits of using intercropping to improve crop disease prevention, productivity, and soil quality (van Leeuwen 2019). Conversely, excessive use of fertilizers and burning of pineapple residues used for intercropping in Johor have negative impacts, but this approach could be improved by removing pineapple waste by hand (van Leeuwen 2019) and valorizing the waste as compost, feed for animals, biogas, or others (Hepton 2003; Seguí and Maupoey 2018). In Pahang, alley cropping in OP plantations facilitated habitat complexity and significantly higher arthropod beta-diversity compared to other traditional monoculture systems (Ashraf et al. 2018). Generally, arthropod orders, but not abundance or composition, were found significantly higher in polyculture than monoculture smallholdings (Ghazali et al. 2016). Planting cover crops such as legumes that form dense low-growing mats also reduces the need to use herbicides to control undergrowth (Samedani et al. 2015).

Modelling studies suggest that intercropping of OP with other crops, in particular cacao, provided high land sparing effects, while also replenishing more ground water and reducing carbon footprint (Migeon 2018; Stomph 2017; Khasanah et al. 2020). Additionally, the implementations of bio farms in Malaysia have been shown to reduce soil nutrients depletion and reduction in chemical use (Howes and Fletcher 2020). This production system improves on standard practices by extending the crop cycle, building soil organic carbon, alternative replanting methods, and minimizing soil loss (Howes and Fletcher 2020).

Biological pest control

Biological pest control agents that prey on rats such as barn owls (Salim et al. 2014; Puan et al. 2011; Saufi et al. 2020), macaques (Holzner et al. 2019), leopard cats (Silmi et al. 2013; Rajaratnam et al. 2007), or snakes and monitor lizards (Lim 1999) may decrease pesticide use and enhance biodiversity in plantations. On top of barn owls that are introduced, high density of other naturally occurring nocturnal bird species recorded in OP smallholdings also posits the potential for these carnivores to act as biological pest controls (Yahya et al. 2020). Ground and epiphytic ferns growing at OP trees constitute nesting sites for insectivorous birds (Koh 2008; Desmier de Chenon and Susanto 2005) that further act as insect pest control (Koh 2008). However, despite their adaptability to the plantations, intact forest patches adjacent to OP plantations remain necessary habitats for the biological pest control agents to rest and breed (Ruppert et al. 2018; Holzner et al. 2019).

Enhanced downstream processing (SDG1, 6–9, 13)

Output diversification

Growing a local palm-based oleochemical industry and moving the local industries up in the commodity value chain, with products spanning from base oleo like fatty acids to end products like polymer and cosmetic products (Salimon et al. 2012), has the potential to further increase the profit margin (Tong 2017), which removes reliance on further plantation expansion. Globally, about 44% of the global vegetable oil (19% from PO and palm kernel oil) was consumed in the chemical industry, with a relatively small amount devoted to biofuel production (Goh 2016). Major oleochemicals produced include fatty acids, fatty alcohols, methyl esters, glycerin, and soap noodles, with prospective markets including highly priced specialty oleochemicals like amino acid esters, and β-carotene that have important applications in the cosmetic, pharmaceutical and food industries (Mba et al. 2015). These specialty oleochemicals are also considered better substitutes for fossil-based chemicals due to their bio-based nature (Basri et al. 2013).

Additionally, there is growing interest in Europe, Japan, and Korea to import OP biomass to substitute fossil fuels for power generation (specifically as an alternative to coal for power generation and district heating in Japan and Korea) (Goh et al. 2019), second generation liquid biofuels, packaging materials as well as drop-in and novel chemicals (Sheldon 2014; Mai-Moulin et al. 2019). Furthermore, these biomass streams can be potentially converted to building blocks (e.g., sugars) for high-value chemicals or substitutes for fossil materials (e.g., bioplastics) (Zahari et al. 2015). Two state-specific strategies were rolled out for Sabah and

Sarawak, under Malaysia's National Biomass Strategy 2020 to develop domestic high value-added biomass-based industries, through valorizing the agricultural residues in combination with municipal solid waste (AIM 2013). The plan was kickstarted with promoting energy pellet production for both local consumption and export, motivated by the Feed-in-Tariff schemes for bioenergy in both Malaysia and overseas markets (Garcia-Nunez et al. 2016).

Waste management and recovery

Waste management practices in plantations impact the air, water, and soil quality of the environment (Gaveau et al. 2014; Truckell et al. 2019). Residues produced in OP mills in Malaysia are around 100 Mio t year-1 (MPOB 2018). Two important residues are the liquid PO mill effluent (POME) and an abundant amount of low value bio-resources in the form of agricultural and forestry residues, such as empty fruit bunches (EFB) and palm kernel shell (PKS) (Truckell et al. 2019). POME disposed from PO mills contains high chemical oxygen demand and biological oxygen demand, thus, it is contained in ponds near to the mills to avoid contamination of water resources (DOE 1974, 1994; MOE 1979). Untreated POME can severely pollute water resources and release large quantities of methane, a major GHG, i.e., 1 t of POME residue can emit 33 kg of methane equivalent to 750 kg of CO_2 (Rupani et al. 2010). However, treated residues composted and neutralized together with EFBs can be used as biofertilizer, whereby they can be returned to the soil to replenish carbon and nutrients through mulching to enhance soil quality in plantations (Truckell et al. 2019; Tao et al. 2017).

Discussion

Increasing recognition of the drawbacks to the rapid expansion of OP as an agricultural sector has led to efforts towards more sustainable practices to mitigate the adverse manifestations of OP industry such as deforestation and human–wildlife conflicts, human rights issues, pollution, and degradation of environmental quality (Tang and Al-Qahtani 2020).

However, perceptions surrounding PO and the OP industry are highly polarized, likely arising from the overemphasis on the negative impacts of irresponsible OP cultivation practices, an anti-PO stance from European and US governing bodies (Choiruzzad 2019; Wahab 2018), and consequently retaliatory stances from PO-producing nations (Liu et al. 2020). Even the literature appears polarized and at times directly conflicting, in particular with regards to nutritional impact of PO consumption on health and the impact of plantation management practices and certification schemes on improving sustainability.

In terms of health, a key limitation in understanding the impact of PO consumption is the fact that most studies are focused on PO as a single oil, or even if compared with other oils, they are rarely designed to observe intake as part of a wider diet. This tends to inflate both negative and positive impacts of consuming PO or its derivatives, depending on study methodology and any underlying biases (Ismail et al. 2018; Di Genova et al. 2018; Sun et al. 2015).

Conflicting views about OP agriculture and impact of sustainable management practices on the environment are often due to missing but important information at various levels making it hard for various stakeholders to understand the complex situation (Gaveau et al. 2016). There is paucity of data on awareness, adoption, and impact of sustainable practices among smallholders and, in particular, indigenous smallholders in Malaysia. Studies of land conversion of peatlands into OP plantations (Edwards et al. 2010; Gunarso et al. 2013) are through estimations or projections that often do not use the same time scale which makes them difficult to compare, highlighting the need for a universal methodological framework for more concerted monitoring of rate of conversion of peatland. Additionally, the literature and most discussions about OP agriculture are skewed towards the Indonesian context and only few studies propose mitigation efforts, especially feasible diversification of existing or rehabilitation schemes of abandoned plantations.

Existing studies aimed at enhancing sustainable practices are widely lacking in depth, long-term data, or demonstrable economic competitiveness, and thus are largely unable to provide applicable and scalable solutions. For example, while Begum et al. (2019) found that millers in Malaysia use efficient and environmentally friendly practices in waste disposal, more research is needed to understand how these practices can be further developed and adopted on a wider scale. Furthermore, the long-term impacts of diverting biomasses for industrial diversification are unclear, and due to logistic constraints, unclear business models, market uncertainties, and fluctuating CPO prices, large-scale mobilization of OP residues and POME treatment systems in rural areas has only been partially realized in the past few years. While data from specific localized studies on reducing forest fragmentation and human–wildlife conflict appear encouraging, the evidence on the broader impact of sustainable certification on improving worker conditions, smallholders and environmental conservation is still being accrued, with effective implementation and transparency being the underlying determinant.

In general, more detailed environmental and bioeconomic impact studies of sustainable vs. conventional PO production are needed to assess the benefits of (certified) sustainable management for the environment and local economy, especially for smallholders. The use of life cycle assessments may better estimate the impact of human activities on the environment, specifically for a commodity chain such as OP (Hashim et al. 2018). As many impacts of PO production on the environment are difficult to quantify, more comprehensive datasets are highly needed to develop better practices for sustainability in the long term (Hashim et al. 2018).

Many studies focus on the impact of OP as a single crop, without comparing these impacts against those arising from other existing and potential crops, which prevents a more contextualized impact assessment. For instance, coconut cultivation practices are less discussed as a driver of biodiversity loss, despite contributing to species loss in many tropical countries (Meijaard et al. 2020). Tackling biodiversity loss in plantation landscapes necessitates a deeper understanding about both positive and negative impacts of OP plantations on different species to develop solutions for environmental, wildlife and human welfare issues. In particular, there is an absence of evidence for mitigating roles of education/awareness, legal enforcement, and general reduced consumption.

Optimistically, the identified key mitigation strategies appear to possess potential co-benefits in advancing efforts for multiple SDG-related goals, with fewer strategies that either are conflicting or trade-offs that detract from efforts to achieve SDGs (Fig. 1). However, the effectiveness and longer-term impact of some mitigation efforts remain unknown.

Conclusion

In many ways, the prevailing conflicting evidence, garnered from single perspectives on this complex issue, further propagates views that are one sided. The different impacts of PO on different aspects of human and planetary health, and the corresponding SDGs, tend to be discussed separately, as are several of the solutions and mitigations efforts proposed. This situation then continues to neglect the complicated aspect of OP agriculture and agriculture in general, which consequently undermines the positive and often necessary socio-economic benefits of these industries to producer countries and the local communities (Gaveau et al. 2016). Moving forward, the varying impacts of PO on sustainability goals must be assessed with the intention to capitalize on the positive interactions and mitigate conflict of goals arising from negative interactions (Nilsson et al. 2018). Improving practices within and surrounding plantations through strategies that combine economic incentives with mitigation of adverse environmental impact may enable farmers and plantations to be part of more scalable holistic sustainable solutions.

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Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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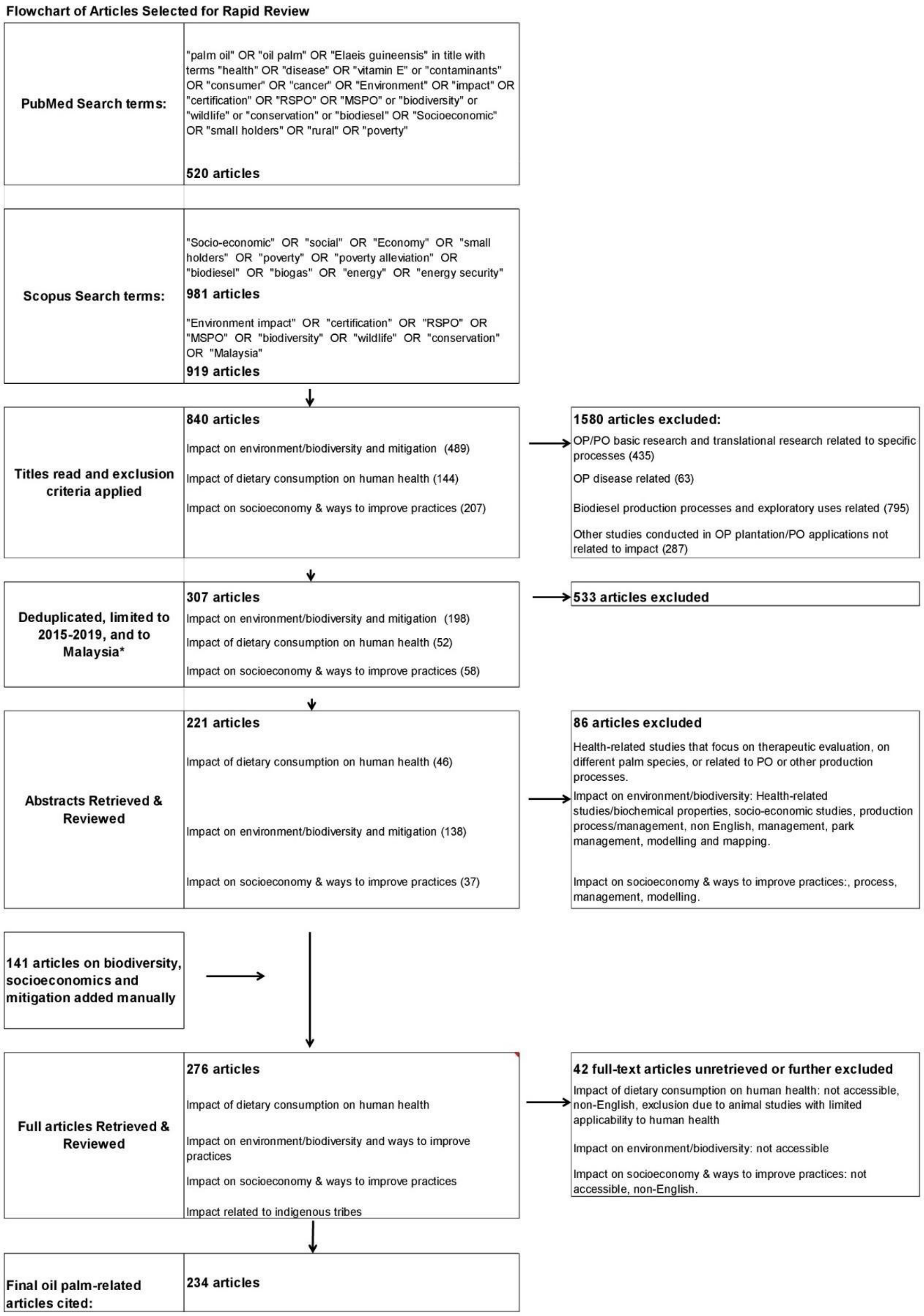
SUPPLEMENT



Flowchart of Articles Selected for Rapid Review

PubMed Search terms: "palm oil" OR "oil palm" OR "Elaeis guineensis" in title with terms "health" OR "disease" OR "vitamin E" or "contaminants" OR "consumer" OR "cancer" OR "Environment" OR "impact" OR "certification" OR "RSPO" OR "MSPO" or "biodiversity" or "wildlife" or "conservation" or "biodiesel" OR "Socioeconomic" OR "small holders" OR "rural" OR "poverty"

520 articles

Scopus Search terms: "Socio-economic" OR "social" OR "Economy" OR "small holders" OR "poverty" OR "poverty alleviation" OR "biodiesel" OR "biogas" OR "energy" OR "energy security"

981 articles

"Environment impact" OR "certification" OR "RSPO" OR "MSPO" OR "biodiversity" OR "wildlife" OR "conservation" OR "Malaysia"

919 articles

Titles read and exclusion criteria applied: 840 articles

Impact on environment/biodiversity and mitigation (489)

Impact of dietary consumption on human health (144)

Impact on socioeconomy & ways to improve practices (207)

→ **1580 articles excluded:**

OP/PO basic research and translational research related to specific processes (435)

OP disease related (63)

Biodiesel production processes and exploratory uses related (795)

Other studies conducted in OP plantation/PO applications not related to impact (287)

Deduplicated, limited to 2015-2019, and to Malaysia*: 307 articles

Impact on environment/biodiversity and mitigation (198)

Impact of dietary consumption on human health (52)

Impact on socioeconomy & ways to improve practices (58)

→ 533 articles excluded

Abstracts Retrieved & Reviewed: 221 articles

Impact of dietary consumption on human health (46)

Impact on environment/biodiversity and mitigation (138)

Impact on socioeconomy & ways to improve practices (37)

→ **86 articles excluded**

Health-related studies that focus on therapeutic evaluation, on different palm species, or related to PO or other production processes.

Impact on environment/biodiversity: Health-related studies/biochemical properties, socio-economic studies, production process/management, non English, management, park management, modelling and mapping.

Impact on socioeconomy & ways to improve practices:, process, management, modelling.

141 articles on biodiversity, socioeconomics and mitigation added manually →

Full articles Retrieved & Reviewed: 276 articles

Impact of dietary consumption on human health

Impact on environment/biodiversity and ways to improve practices

Impact on socioeconomy & ways to improve practices

Impact related to indigenous tribes

→ **42 full-text articles unretrieved or further excluded**

Impact of dietary consumption on human health: not accessible, non-English, exclusion due to animal studies with limited applicability to human health

Impact on environment/biodiversity: not accessible

Impact on socioeconomy & ways to improve practices: not accessible, non-English.

Final oil palm-related articles cited: 234 articles

Figure S1. Flowchart of Literature Search and Review following PRISMA (http://www.prisma-statement.org/) guidelines. The terms "palm oil" and keywords, and additional terms related to the scope of the review such as “environment”, “biodiversity”, “consumer”, “poverty”, and “health” were searched in PubMed and Scopus from April 2019 – July 2020. The initial criteria for inclusion were articles published after 2000, in English language, and related to PO and the aforementioned areas. Titles of articles were reviewed, and articles were first excluded based on the following criteria: 1) Limited to technical processes in PO production, or on OP plant diseases; 2) Limited to specific methodology and/or basic scientific research in OP/PO with limited conclusions; 3) Focus on biodiesel production processes and exploratory uses of PO; and 4) Other studies conducted in OP plantation/OP applications not related to impact. Additional relevant publications beyond the search dates were added manually as indicated in the figure.