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Utilization of Palm Oil and its By-Products in Bio-asphalt and Bio-concrete mixtures: A Review

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Abstract

This research aims to discuss the utilisation of crude palm oil (CPO) and by-products obtained from palm oil waste materials as biomaterials for green construction material applications. The oil palm frond, empty fruit bunches, mesocarp fibre, palm kernel shell, and oil palm trunk, as well as CPO, which is the primary product in the palm oil industry and has a variety of uses in the production of food and non-food items such as cooking oil, biodiesel, and cosmetics, are all products of the palm oil tree and have been used in several asphalt pavements and building construction applications after further processing to produce highly efficient bio-products. The manufacturing process, characteristics, motivations, and challenges associated with using palm oil and other palm tree waste products as a substitute material in asphalt pavement and concrete materials are explored here to better understand palm-based green bio-materials for sustainable construction. It was discovered that CPO and its by-products could be used to make sustainable and cost-effective asphalt and concrete as they're more renewable, environmentally friendly, and safer to handle than petroleum-based binders, and they produce concrete effectively when palm oil fuel ash (POFA) and palm oil clinker (POC) are used. However, using CPO in pavement construction has challenges, such as securing palm oil as a feedstock for non-food items and collecting enough palm oil for edible oil to maintain food and energy security, particularly in countries that do not produce CPO.

Keywords: Palm oil, Biomass, Palm oil waste materials, Bio-asphalt binder, Concrete mixtures

1. Introduction

Replacing petroleum-based bitumen with bio-binders has elicited extensive interest from bitumen industries, governments, and researchers [1, 2]. Oil palm (*Elaeis guineensis*) is extensively grown in Southeast Asia and Equatorial Africa [3]. Palm-nut contains two types of oil, namely, crude palm oil (CPO), which is extracted from the outer core of the palm nut, and palm kernel oil, which is obtained from the inner core [4]. CPO is the primary product derived from the red fruits of oil palm. The chemical characteristics of CPO differ across countries and regions; however, palm oil commonly contains 45% palmitic acid, 40% oleic acid, 10% linoleic acid, and 5% stearic acid [5]. CPO is a versatile and important raw material for the manufacturing of food and non-food products, such as cooking oil, biodiesel, and cosmetics [6, 7], and contributes 30% to global oil production. Fig. 1 shows the production amount of palm crude oil (PCO) and palm kernel oil (PKO) in Asia, Africa, and the world from the year1966 to 2014 based on food and agriculture organization (FAO). It is evident that Asian palm oil fruit extracts are the highest in world production [8].

The United States Department of Agriculture reported that the production of palm oil was 64.5 million metric tons in the year 2016 and 2017. Southeast Asian countries are the primary palm oil producers [9]. Malaysia and Indonesia produce about 80% of the total palm oil in the world. About 90% of produced palm oil is exported to countries around the world [4, 10, 11]. According to FAO and Malaysian Palm Oil Board, the total area utilised for palm oil production in the world in 2018 was 18.92 million hectares (13.86 million ha more than in 2006), with Indonesia having 6.78 million ha (4.11 million ha more than in 2006) and Malaysia having 5.24 million ha (4.17 million ha more than in 2006) [8, 12]. Compared to other vegetable oils, palm oil has the highest yield quantity in the international market [13]. Fig. 2 shows the distribution of global oil production in 1990 and 2011. Since the development of biofuels such as biodiesel is one major strategy in this area, the massive volume of palm oil produced may be used in various biofuel-related applications, such as bio-asphalt production, bio-concrete and other bio-construction materials and technologies.

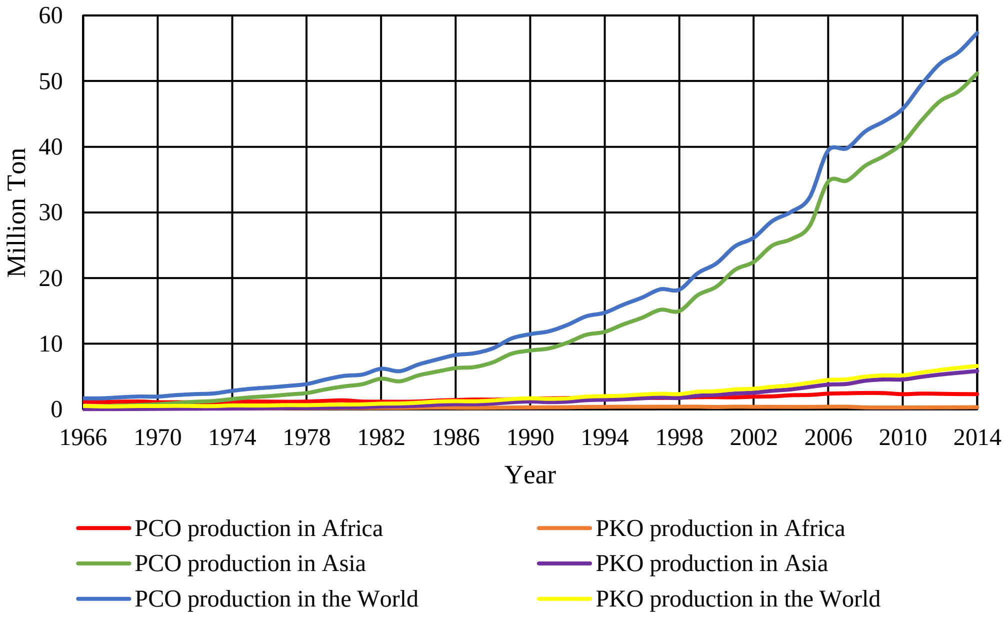

Fig. 1. PCO and PKO production in Asia, Africa, and the World [8]

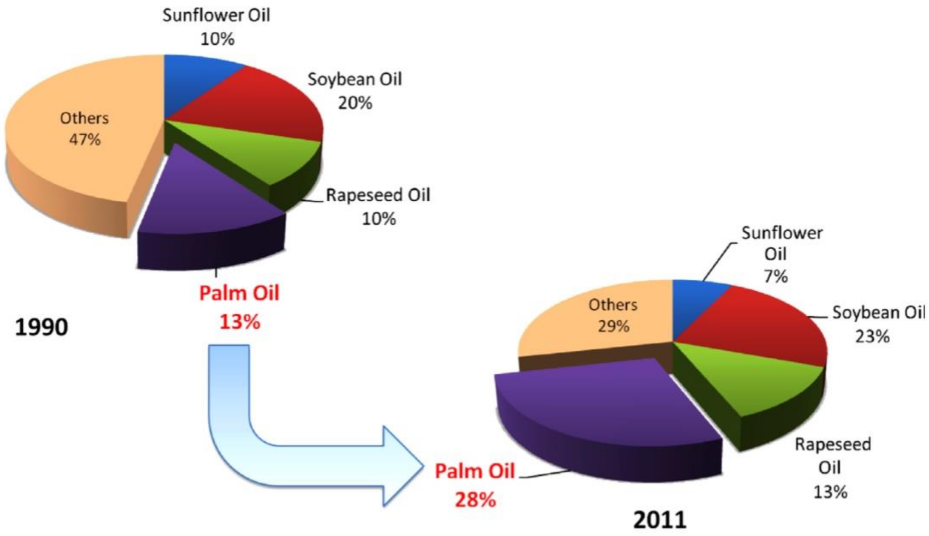

Fig. 2. Distribution of global oil production in 1990 and 2011 [14]

Most of the currently available biodiesel is produced from edible oils, such as sunflower, rapeseed, soybean, and palm. Around 28 million tons of biodiesel were produced from edible oil in 2014. Biofuel derived from biological systems generally has properties similar to those of petroleum-based diesel; the difference between the two is that biofuel is non-toxic and made of biodegradable materials, which potentially reduce greenhouse emissions. Therefore, biodiesel is seen as an environmentally beneficial, sustainable, and long-term alternative to petroleum-based fuel [11]. In comparison to other feedstocks used as biomaterials for biofuel production, palm oil offers greater potential and benefits as a feedstock for biofuel production. Unlike rapeseed and soybean, palm oil is a perennial crop, which means this oil is continuously and uninterruptedly produced. Compared with rapeseed, soybean, and sunflower oil plantations, palm oil plantations have higher oil yields, as shown in Fig. 3. Palm oil that is exported from Malaysia to Europe is equivalent to 1.7 million ha of rapeseed or 4.9 million ha of soybeans [15].

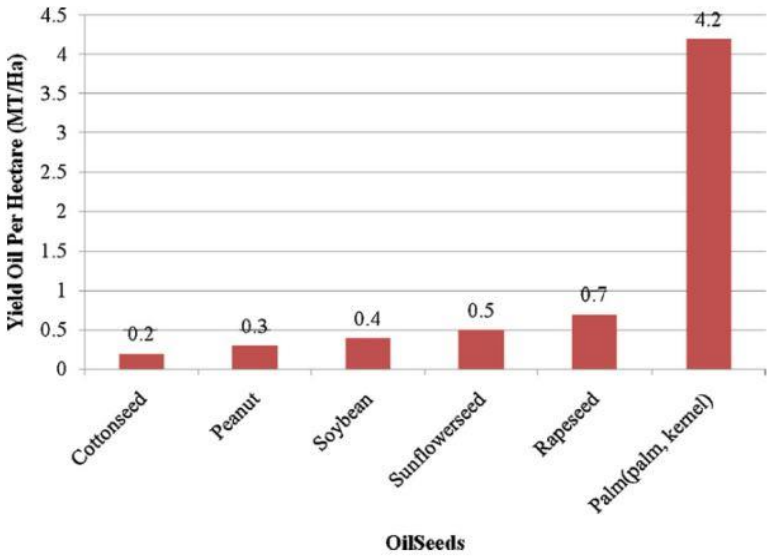

Fig. 3. Yield compression of common oilseeds [15]

Even though the tonnage of the major oilseed production shows only 3% for palm kernels and 59% and 62% for soybean for the years 2017/2018 and 2020/2021, respectively (based on FAO data) as shown in Fig. 4, oil yields tonnage per hectare shows otherwise, with palm oil (crude and kernel palm oils) yielding 54% oil and soybean yielding only 9% oil as illustrated in Fig. 5.

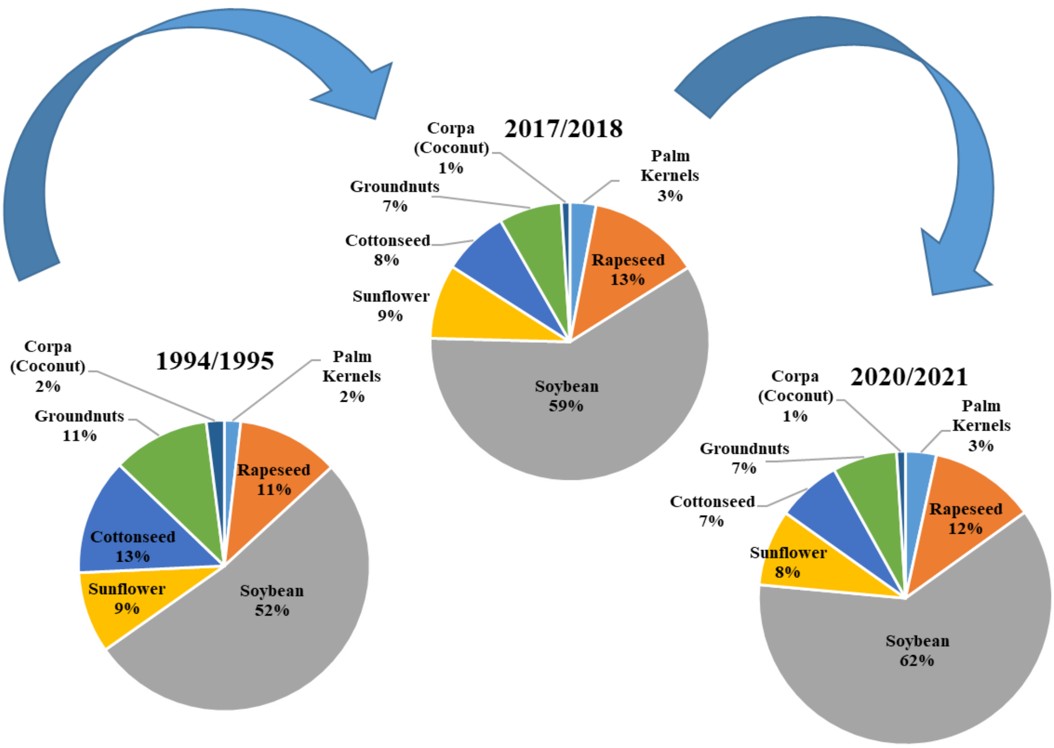

Fig. 4. Tonnage percentage of major oilseeds produced in 1994/1995, 2017/2018, and 2020/2021

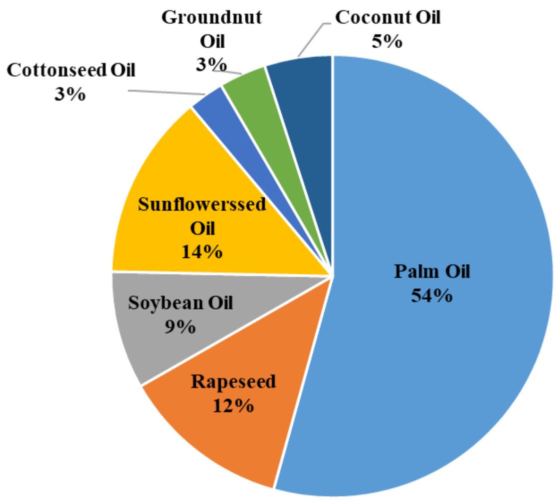

Fig. 5. Tonnage per hectare percentage of major corps oil yield in 2018

However, huge amounts of CPO are produced worldwide, but there is a very small body of research that has applied CPO as a partial or total replacement for bitumen. Similarly, there are very few studies reported to investigate the possibility of using CPO in different concrete and construction materials technologies. Therefore, the present study aims to review relevant literature and introduce CPO as a biomaterial that can be incorporated in asphalt pavement and concrete mixtures technologies to contribute to the production of durable, environmentally friendly, cost-effective, and sustainable construction materials.

On the other hand, the huge quantities of palm oil produced annually come up with a large number of waste materials being disposed into landfills. Therefore, in order to reduce the negative impact of such waste materials, they are used as an additive and particularly replacement for cement and bitumen in construction materials [16].

Over the years, the number of published articles in some of the most reputable publishers that incorporated palm oil and its by-products in concrete and asphalt mixtures has grown steadily. Fig. 6 shows the number of articles in the field of concrete, and Fig. 7 shows the number of articles in the field of asphalt. It can be observed that most published research has been in the field of concrete mixtures, with little on asphalt mixtures which are considered a hot research gap that needs to be further studied.

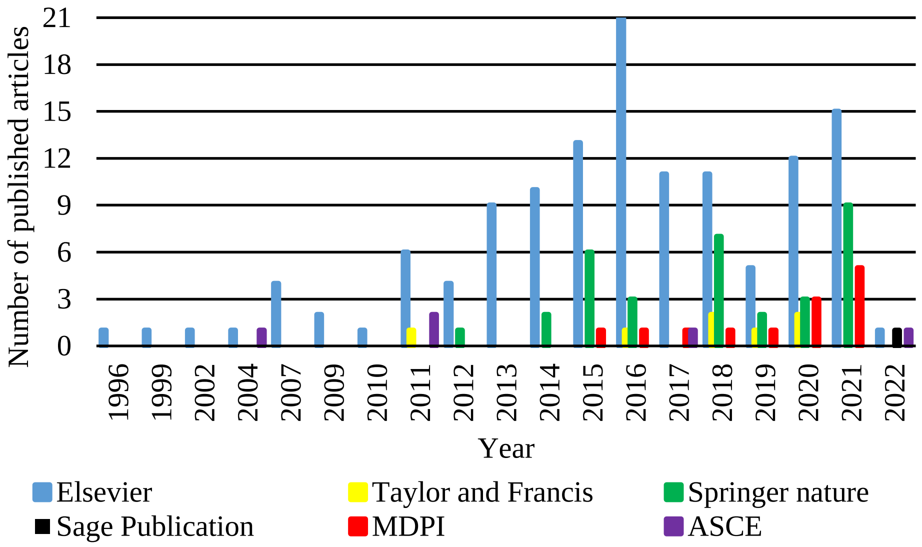

Fig. 6. The research trend of bio-concrete that incorporates palm oil by-products

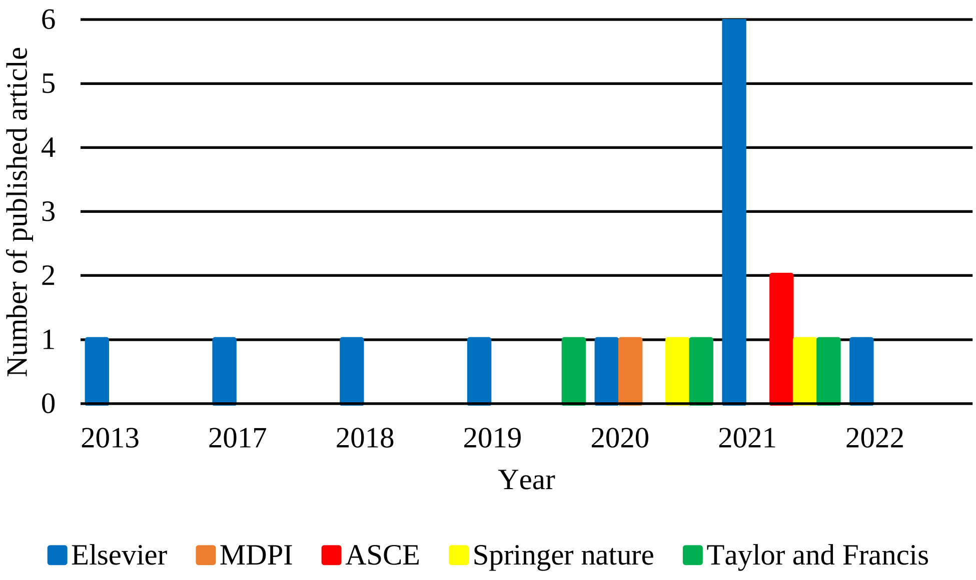

Fig. 7. The research trend of bio-asphalt pavement that incorporates palm oil and its by-products

2. Environmental and sustainability aspects of using palm oil

Pirker et al. (2016), discussed how climate, soil, and topography all contribute to a land's potential for oil palm plantation. It was stated that climate demands annual precipitation of 1000-5000 millimeters per square meter, several dry periods ranging from 0 to 4 months, an average annual temperature of 18-38 °C, and a minimum temperature of more than 15 °C in the coldest month. For planting, it is required different types of soil of sand, clay, and loam, as well as a slope of 0 to 25% and an elevation ranging from 0 to 1500 meters. Generally, there are 1.37 billion hectares of land suitable for palm oil tree plantation as presented in Fig. 8 [17-19]. Even though the most suitable locations can be identified by geographical aspects, Tapia et al. [20], who applied fuzzy logic to classify land areas for palm oil cultivation in Malaysia and Indonesia, believe that innovative decision-making tools are needed to aid in the identification of suitable yet ecologically friendly areas, as well as the development of evidence-based policies for establishing a sustainable palm oil sector.

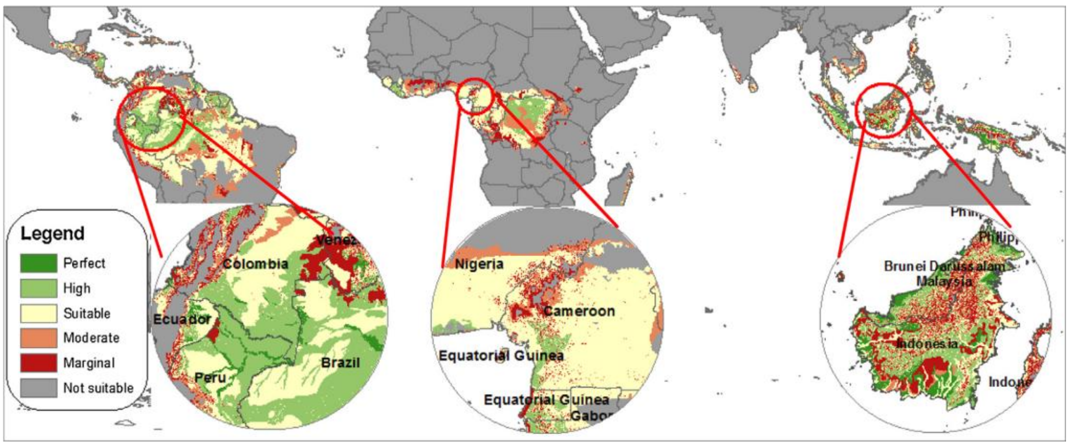

Fig. 8. Global suitability map for oil palm tree plantation [17]

While palm oil plantation offers a great deal of area of opportunities for other industries, the palm oil industry itself plays an important role in releasing a large number of Nitrogen dioxides (NO_2), Sulphur (SO_2), Carbon monoxide (CO) that are harmful to the environment and natural ecosystems. Another negative impact of this industry is deforestation in Indonesia, Malaysia, and Thailand which are top producers among other countries [21]. According to Saswattecha et al. (2015), five actions significantly contribute to the environmental impacts of CPO production: 1) fibre burning in boilers, 2) fertiliser use, 3) wastewater treatment and empty fruit-bunch disposal, 4) gasoline use in weed cutters, and 5) glyphosate use for weed control. Together, these activities contribute to environmental concerns such as global warming, ozone layer depletion, acidification, and human toxicity [22].

Saswattecha et al. (2017) examined four different scenarios for reducing the environmental impacts of increased palm oil plantations in Thailand by 2050. They discovered that only the green-development (GRN) scenario, which assumes implementation of a mixture of effective ways regardless of their cost, significantly reduces environmental impacts. The scenario allows expanding the area of plantation by 1.7 million ha by 2050 and an increase of up to 35 ton/ha of FFB yield by 2050. This benefits biodiversity protection as well as carbon storage while causing the least amount of damage to other crop output. This reduction is mostly due to EFB combustion, which avoids significant quantities of CO_2, SO_2, and NO_x emissions while increasing Volatile organic compounds (VOC), CO, and particulate matter (PM) emissions. Additional steps at the EFB-combustion plant should be investigated as well, to decrease VOC, CO, and PM emissions. The authors also discussed how the GRN may be hard to implement since it ignores the expenses associated with deploying mitigation measures. In this regard, the strong-growth (GRT) scenario may be more viable. The latter scenario envisions a rapid rise in palm oil exports while adhering to international sustainability guidelines (RSPO). This scenario allows for expanding the area of up to 3.4 million ha by 2050 while maintaining the same yields by 2050 [23].

Apart from deforestation, orangutan extinction and peatland destruction continue to be challenges associated with palm oil planting in certain tropical locations. However, with the global population expected to reach 9.7 billion by 2050, only palm oil is capable of providing the fats and vegetable oils necessary to feed the world's population. India and China are two recent instances of high-population countries that are also significant importers of palm oil [24, 25]. To move towards economic, social, and environmental sustainability, an optimum efficiency approach should be pursued that requires policies and strategies. Banks and investors, environmental and social non-governmental organizations (NGOs), Oil palm growers, traders, manufacturers, and retailers set up an association called Roundtable on Sustainable Palm Oil (RSPO) according to article 60 of the Swiss Civil Code. RSPO has 16 executive members and more than 5,000 members at the time this paper is being written and it aims to enforce its members to apply sustainability for palm oil plantations. However, there are still many concerns about the plantation of oil palm plantation in larger areas such as destroying any forest not identified as high conservation values (HCV) and high carbon stock (HCS) [25].

Chavalparit (2006), evaluated Thailand's route to a more sustainable and cleaner CPO production and a zero-waste industrial environment and identified four factors as hurdles. Firstly: Informational barriers that do not allow to gather and disseminate information. The absence of any governmental institution effectively supporting research and technological development in the palm oil industry is a significant hurdle to moving the CPO sector towards sustainability. Secondly: collaboration barriers. Without structured coordination among relevant entities, information sharing will fail. For clean technology adoption and waste exchange in Thai CPO mills, lack of collaboration between mills and other players including research organizations and associations is a serious obstacle. One cause for the limited collaboration is the lack of vertical integration in the palm oil-producing economic networks. Thirdly: Pricing barriers. Thailand's environmental policies are based on command and control. These restrictions provide little motivation for mills (particularly those located distant from towns) to improve their manufacturing processes or to lower emissions below statutory requirements since there is no (economic or social) benefit for doing so. And lastly: Human capacity barriers. Human capacity shortages (both quality and quantity) within government and industry are major barriers to clean technology implementation. Thai environmental regulations mainly depend on governmental command and control mechanisms implemented on enterprises [26].

Chew et al. [27] mentioned that to have a more sustainable palm oil production and reduce the land plantation area, increasing the oil extraction ratio (OER) can be an important measure. One way of increasing OER is by increasing residual oil recovery of EFB, palm pressed fiber (PPF), and palm oil mill effluent (POME) from the waste streams. However, due to the problems associated with environmental risks of using solvents for oil extraction, this method is not favorable. Another approach of increasing OER is to increase oil extraction or reduce the oil loss by decoring, enzyme technology and acoustic irradiation, and Maceration induced cell rupturing oil nut extraction synthesis (MICRONES) system, which is very promising. Apart from the palm milling production improvements that lead to the more sustainable production of palm oil, other by-products of the palm oil industry play important roles in the environmental and sustainability of oil palm milling. Wastes from the oil palm tree are used in different industries such as the production of glucose, bioethanol, pulp and paper industry, biofuel production, construction industry, and other biomaterial industries. Since the development of the palm oil industry in suitable regions is inevitable, the above-mentioned industries are going to develop further. Some benefits of using palm oil and turning its by-products into useful materials (Such as palm clinker fuel ash, palm oil clinker, and bio-oil) in the construction industry is the possibility of reducing the use of virgin materials while improving the structural performance of concrete and asphalt mixtures, reducing the impacts of oil palm industry wastes in the environment [28-31].

3. Manufacturing of palm oil and its derived materials

The palm tree is ready to be harvested after approximately 3 to 4 years from the plantation [32]. As seen in Fig. 9, during the harvesting, fresh fruit bunch (FFB) is processed in the palm oil milling, and two types of oils are extracted in this stage CPO and PKO. Other wastes from the palm tree, such as oil palm fronds (OPF), oil palm trunk (OPT), palm kernel shell (PKS), empty fruit bunches (EFB), and mesocarp fibre (MF), will subsequently be processed further through the pyrolysis (To produce pyrolysis bio-oil) and burning processes (To produce OPFA and POC). In addition, Terry et al. [33] reviewed the production of palm bio-oil through the pyrolysis process and revealed that the bio-oil yields are higher in EFB and OPF than OPT, MF, and PKS when the process is performed around 450 °C. Figure 5 illustrates the process of producing CPO, bio-oil, and oil palm waste materials for different construction materials applications. Fig. 10 also explains the effects of the pyrolysis temperatures on the bio-oil yield from different oil palm waste materials. MF and OPT show the highest temperature required with the intermediate yield bio-oil. In contrast, EFB show the highest yield bio-oil at around 400 °C, which makes it one of the best alternative waste materials that can be applied to produce the bio-oils for construction materials with considering the lower energy consumption, cost-effective and sustainable.

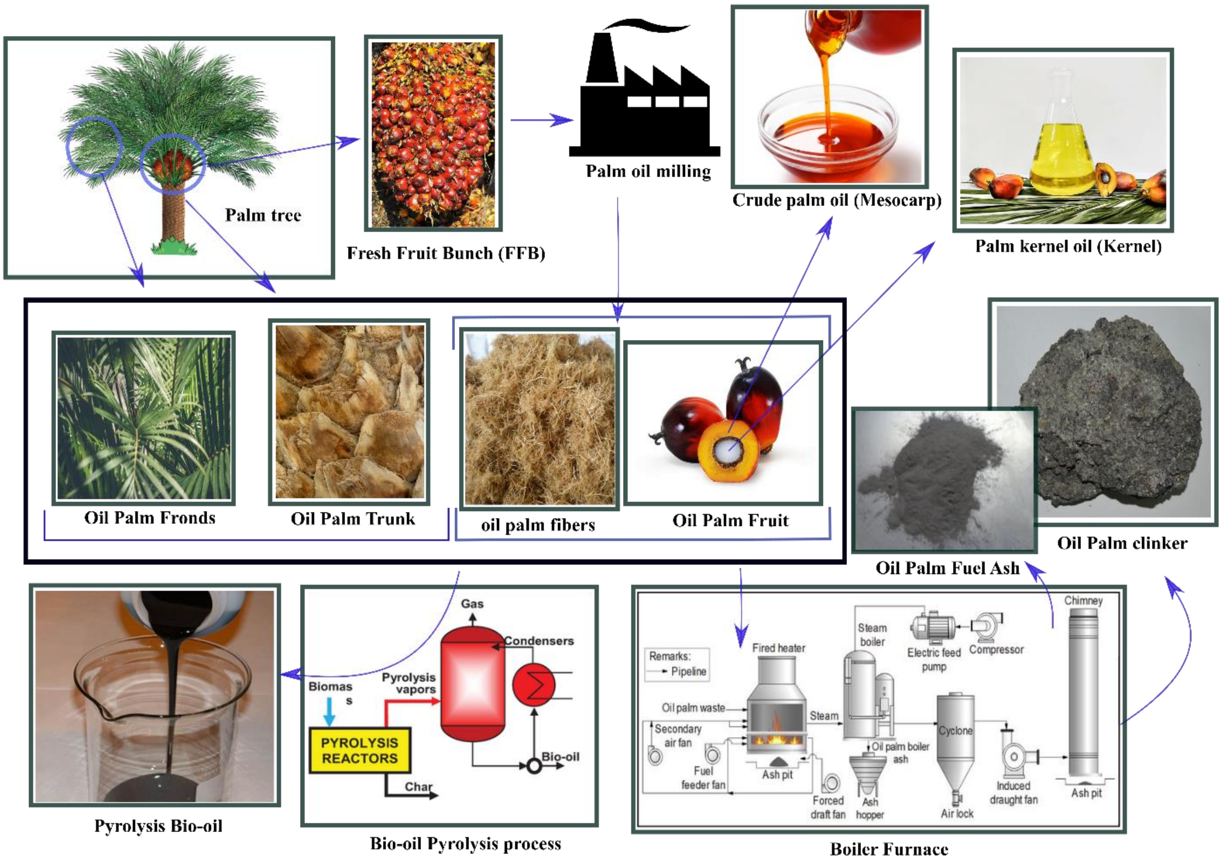

Fig. 9. The process of producing CPO, bio-oil, and oil palm waste materials for different construction materials applications [34-37]

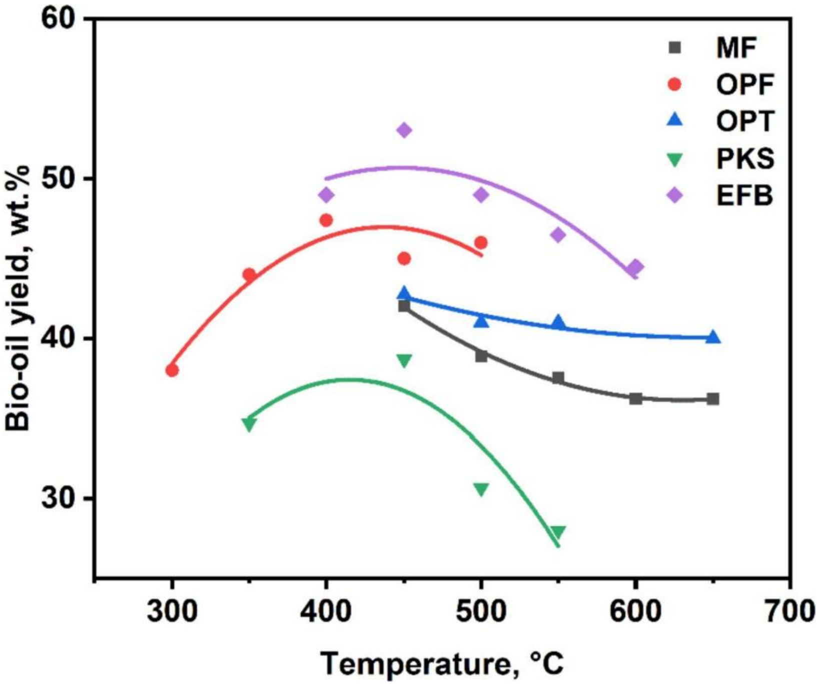

Fig. 10. Bio-oil yield as a function of oil palm waste materials and pyrolysis temperature [33]

4. Application of palm oil in biofuel

In this review, the production of biofuel from oil palm products and their by-products has been highlighted for its direct correlation with the production of bio-construction materials, particularly bio-asphalt. Most of the raw materials that have been used successfully for producing biofuel can be investigated as bio-oil for asphalt and cementitious materials. Malaysia began producing biodiesel from palm oil more than a decade ago. Around 500,000 tonnes of biodiesel were produced during 2006, and output is likely to rise as palm oil is inexpensive (MYR 1.4) compared to expensive petroleum-based diesel (MYR 2.10) [5]. Domestic palm oil production in Malaysia is expected to reach 26.6 million tons in 2035, and approximately 1.4 million tons will be used for biofuel. Nearly 30% of the total global biodiesel feedstock is produced from palm oil [6]. In comparison to other biomass-based biofuels like soybean, rapeseed, and sunflower, palm oil trees provide a greater energy yield. For instance, approximately half of Indonesia's renewable energy consumption would come from biofuel by 2030, with 24% coming from liquid palm oil bio-fuel [38]. Currently, researchers and the green energy industry are looking and extensively investigating the different technologies that can be used to maximize the production of biodiesel from the different vegetable-based oil including crude palm oil. Fig. 11 shows the importance of palm oil as a feedstock for biofuel among the other vegetable oils that have been investigated for the production of biofuel worldwide. Therefore, it can be said that palm oil and its by-products could be one of the sustainable alternatives and the innovative materials to be investigated and used in construction materials for improving the different properties and performances.

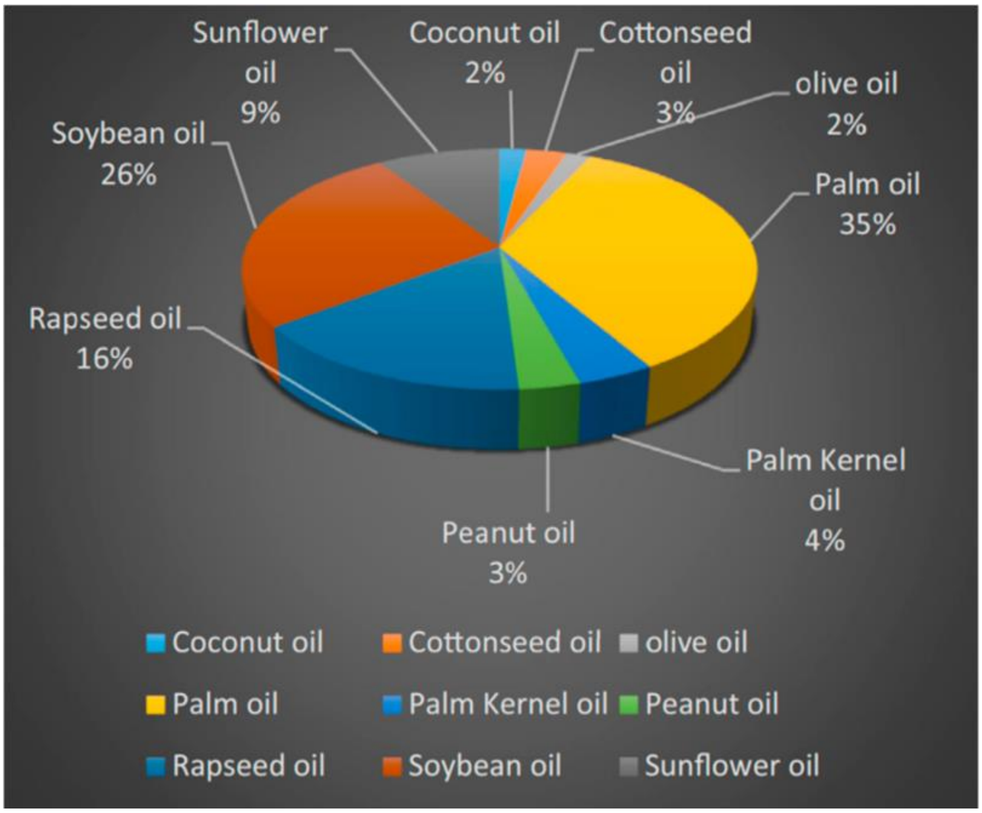

Fig. 11. Percentages of different vegetable oils production as a feedstock for biofuel [39]

5. Application of palm oil and its by-products in asphalt pavement

Palm oil and its by-products have been attracting the attention of research during the last few years, notably in the field of pavement materials, due to their long-term sustainability and widespread availability. Crude palm oil , palm kernel oil, palm oil clinker, oil shale, palm shell, palm oil fuel ash, fast pyrolysis bio-oil, and palm oil boiler ash are the common palm oil products and by-products that have been studied as shown in Fig. 12. According to VOSviewer mapping, the most common types of palm oil utilised in asphalt binders are crude palm oil and fast pyrolysis bio-oil for the production of bio-asphalt binders. However, the majority of palm wastes such as palm clinker oil, palm oil fuel ash, oil shale, and palm shell are used in asphalt formulations as additives or partial replacements for fine materials in asphalt mixtures.

4.1 Studies on palm oil as a bio-binder in asphalt pavement

Palm oil was one of the best options to be utilised as bio-oil in bio-asphalt binders due to the high level of interest among researchers and industry in developing a sustainable alternative to conventional asphalt. At concentrations of 0%, 5%, 10%, and 15% wt., ~~crude palm oil~~ CPO was studied as a substitute material in the preparation of bio-asphalt binders [40, 41]. It was found that increasing the CPO content results in a decrease in the complex modulus (G*) and an increase in the phase angle (δ) of bio-asphalt binders, which is attributed to the high proportion of lightweight components in bio-oil.It was also found out that the addition of up to 5% of CPO to asphalt binder maintains similar G* and δ of base asphalt at high temperatures and is most likely to enhance the rutting resistance. This was attributed to the high palmitic acid in CPO that acts as a biopolymer at the mixing temperature of CPO and base asphalt resulting in adequate viscosity and stiffness of bio-asphalt. On the other hand, the addition of more than 5% of CPO could improve the fatigue characteristics of asphalt binders. RTFO-aged CPO modified binders also showed that with the increase in CPO, G* decreases and δ increases, which is due to the high amount of aromatic in the bio-oil. The effects of palm oil as a biopolymer in asphalt matrix at high temperatures due to the polymerization were also stated and reported in other studies such as [42, 43].

Waqas et al. [44] investigated the effect of adding ~~a~~ different percentages of CPO and reclaimed asphalt pavement (RAP) on the physical, mechanical, and morphological characteristics of hot mix asphalt. They reported that the addition of CPO in RAP binders increased the penetration and decreased the softening point followed by a reduction in viscosity due to the high aromatics content in the CPO. They also reported that the predicted mechanical performances including stability, flow, stiffness, voids in mineral aggregate (VIM), voids filled with asphalt (VFA), and indirect tensile strength (ITS) all had R^2 of over 0.8 using the ANOVA test. The study found that in order to achieve a RAP modified mixture that both satisfies Malaysian Road standard requirements (JKR) and leads to usage of the high amount of RAP materials (76%) for the above-mentioned mechanical performance, the addition of 9.39% of CPO was suitable. The addition of CPO to RAP and control binders developed a new microstructure captured by Atomic Force Microscopy (AFM). Also, Uchoa et al. [45] studied the rheological and chemical properties of bio-asphalt binders containing 3% of hydrogenated palm oil fat (HPF) and hydrogenated palm fat amide (FAA) as additives to PEN 50/70 binder. The bio-asphalts showed acceptable thermal resistance and a softer type of asphalt, enhancing workability and lowering mixing (by 7.5 °C and 9 °C, respectively) and compaction temperatures (by 6 °C and 5.5 °C, respectively). Both additives exhibited a higher complex modulus (G*) of the modified binders at lower temperatures of 4 °C to 15°C to the same extent compared to the neat binder. That was attributed to the crystalline phase of both additives still present at the lower temperatures. As the temperature increased to the range of 15°C to 25°C, G* decreased significantly for FAA-modified bitumen while HPF-modified bitumen showed a slight reduction in G* which could be due to the change in the structure of the additive due to reaching the softening points of oils. At a temperature of 30 °C, both FAA and HPF modified bitumen show an increase in phase angle (reduction in elasticity), however, the reduction in elasticity was more sensible for HPF modified bitumen. After 30 °C, rheological change in terms of elasticity was not significantly changed except for FAA-modified bitumen that showed higher elasticity at a temperature range of 55°C to 64°C. The findings discussed above were supported by multiple stress creep recovery (MSCR) results that showed higher non-recoverable creep compliance (J_{nr}) of the modified binders compared to base asphalt at a temperature range of 52°C to 76°C.

Alamawi et al. [46] investigated the physical, thermal, and chemical properties of palm kernel oil polyol (PKO-p) bio-based asphalt as an alternative to conventional asphalt. The mixing and compaction temperatures of bio-asphalt binders were reported to be 10% lower than those of base binders, while the viscosity of both types of binders was consistent. The thermal sensitivity of bio-asphalt binders was found to be comparable to that of conventional asphalt, with only a slight difference in weight loss. Chemical analysis revealed that bio-asphalt binders were distinctly different from base bitumen in terms of functional groups. Similar results were obtained when polyurethane (PU) produced from palm kernel oil was studied as a partial replacement for base asphalt binders [47]. It was confirmed that PKO-p significantly improved the rheological properties of base asphalt at high and intermediate temperatures and the optimum PKO-p content was found to be 3 wt%. The enhancement of rutting and fatigue performance of bio-asphalt at various temperatures was attributed to the enhancement of the viscosity, stiffness, and elasticity of asphalt due to the interaction of PKO-p in the asphalt matrix.

The engineering and leaching properties of asphalt binders that were modified with 3% polyurethane (PU) derived from palm kernel oil and 5% Cecabase as a warm mix asphalt (WMA) additive were investigated by [47]. It was reported that PU significantly improved the viscosity of binder and adhesion properties of WMA mixtures which were attributed to the enhancement of binder stiffness and the elastic network constructed in the asphalt matrix. However, it was found that both additives did not lead to crystalline structural changes. Both additives also showed significant improvement in the workability of the binder at lower temperatures. The number of heavy metals leached out from both modified binders showed no environmental impact and was not exceed the limits of standards. The aforementioned discussion exhibited a possibility of using bio-oils derived from palm oil as a modifier in asphalt binders with adequate performance and sustainable properties.

It is well known that at lower and intermediate temperatures, bio-asphalt binders demonstrated promising results; however, they negatively influenced rutting resistance at higher temperatures. To investigate the characteristics of bio-rubberized asphalt binders, the linear and non-linear rheological properties of tyre pyrolysis oil-modified bio-asphalt were investigated at elevated temperatures by other researchers [48]. It was reported in the combination of tire pyrolysis oil (TPO) and CPO improved the viscosity, stiffness, and modulus of composite binders up to 5% CPO and 15% TPO. That improvement was due to the chemical interaction between the TPO and CPO in the asphalt matrix which resulted in a new structure. That 20% of base asphalt could be substituted with 5% CPO and 15% tyre pyrolysis oil (TPO) while maintaining the base asphalt's performance grade. It was also claimed that all composite binders showed significant improvement in aging resistance compared to base asphalt which could be due to the high oxidation resistance of palm oil [5]. Bio-asphalt with 5% CPO and 5% TPO showed the lowest J_{nr} and highest percentage of recovery among all tested binders with PG64H performance grade compared to the base asphalt with PG64S. This indicates the lower strain sensitivity and higher elasticity of composite binders contained 5% CPO and 5% TPO.

Al-Sabaeei et al. [49] carried out a new study on physicochemical, rheological, and microstructural of bio-asphalt binders modified with nano-silica (NS). NS particles are used as a physical treatment for CPO prior to being mixed in asphalt to enhance the viscosity and adhesion properties of bio-oil. The results indicated the homogenous distribution of NS particles inside the bio-asphalt matrix and a considerable improvement in bio-asphalt's physical, rheological, and chemical properties before and after aging. This is due to the compatibility of NS particles with bio-oil derived from CPO, which results in a composite material with characteristics similar to those of petroleum-based asphalt. In detail, NS showed a significant increase in the viscosity, G*, rutting parameters, and percentage of recovery and decrease in δ and J_{nr} which improved the performance grade of modified binders at high temperatures. That could be attributed to the characteristics of NS particles such as desired particle size, polarity, large surface area, adhesion properties, chemical interaction in bio-asphalt binder matrix which results in chemical and microstructural changes that lead to better elasticity and rheological performance compared to base and bio-asphalt binders. In general, bio-oil derived from palm oil was shown to be competitive with petroleum-based asphalt binders. Table 1 summarizes most of the studies that were reported in the literature which are relevant to using palm oil as a bio-oil in bio-asphalt technology.

4.2 Application of palm oil by-products in asphalt pavement

Borhan et al. (2010) [50] investigated the performance of asphalt mixtures containing 0%, 1%, 3%, 5%, and 7% POFA by weight of the mineral filler. Marshall stability and resilient modulus, as well as other tests including dynamic creep, static creep, and fatigue testing, were measured for the mixture's performance. In comparison to the control asphalt mixes, the asphalt mixtures containing POFA demonstrated increased rutting resistance. Another research [51] was conducted to explore the effects of POFA on the performance of the pervious concrete pavement. When the POFA content increased, the permeability and void content of the pervious concrete pavement increased, while its tensile and compressive strengths decreased. POFA also had a minor influence on skid resistance. The optimal POFA content required to meet the American Concrete Institute's environmental and technical criteria was determined to be 20% by weight of cement. The effects of waste palm oil fibre (WPOF) on the performance of stone mastic asphalt mixture were studied using both traditional and sequential mixing procedures [52]. Overall, WPOF was found to improve the characteristics of stone mastic asphalt mixes under both conditions. However, mixtures prepared using the sequential mixing process demonstrated superior mechanical properties at lower bitumen contents than mixtures prepared using the traditional mixing process, which is believed to be due to an adequate aggregate coating and proper dispersion of mixing materials during the mixing process.

Lately, palm oil clinker (POC) was utilized as fine aggregates substitute in stone mastic asphalt (SMA) mixtures at concentrations ranging from 0% to 100% [16]. SMA mixtures containing between 40% and 60% POC showed an increase in mechanical properties such as resilient modulus, rutting resistance, tensile strength, and resistance to moisture damage compared to control and other SMA mixtures. Yaro et al. [53] confirmed the previous research findings and reported that POC might be utilised to make stiffer and greener bitumen than traditional bitumen while also mitigating contamination of the environment caused by such industrial waste materials. Another study investigated the use of palm oil fuel ash as fillers ranging from 0% to 100% in HMA mixtures [54]. It was found that introducing up to 25% CPO ash to asphalt mixtures enhanced their Marshall stability, but adding more fillers would decrease their Marshall stability. The reduction in stability was justified by the presence of higher air voids in mineral aggregates when CPO ash was used more than 25%, affecting the volumetric parameters of the mixes. These findings are consistent with another study that found that utilizing oil palm mesocarp fibre ash (OPMFA) as a filler replacement up to 5% in asphalt mixtures fulfilled Nigerian specification standards for Marshall stability and flow [55].

Gatot et al. [56] investigated the feasibility of using oil palm fruit ash (OPFA) as a modifier for asphalt binder. OPFA was added to the base asphalt at a rate of 2.5% to 15% by weight of bitumen, with a 2.5% increase rate. The physical, dynamic shear, bending beam rheometer, and direct tensile strength characteristics of the OPFA-modified binders were examined by testings. OPFA enhanced the performance of the base asphalt, and OPFA-modified asphalt binders were classified as having a performance grade of PG 70-16. The authors noted that the use of OPFA as an asphalt modifier is practicable. Meanwhile, Zulkefli et al. [57] evaluated the physical properties of modified bitumen containing different amounts of POFA (i.e., 0%, 5%, and 7%) by weight of the base bitumen at various grinding times (1 and 4 hours). The research revealed that the fineness of POFA had a substantial influence on the bitumen's characteristics. When the POFA was increased, the penetration value decreased, and the softening point increased. The most significant results were achieved at 7% POFA with particle sizes ranging from 500 nm to 3 µm, rather than 3 to 7 µm. However, another research asserted that grinding duration and POFA content did not affect the physical properties of bitumen [58]. Usman et al. [59] examined the possibility of using POFA in place of filler in cold mix asphalt (CMA). It was found that the addition of POFA significantly improved the mechanical properties and resistance to moisture damage of CMA. This was linked to POFA's high silica concentration, which enables it to perform as an excellent pozzolana.

Date palm oil was employed as a bitumen modifier at concentrations ranging from 0% to 10% by weight of bitumen to study the effects on the compressive strength of asphalt mixture [60]. It was discovered that date palm oil considerably improved the durability and performance of bitumen and that the modified asphalt mixture met the requirements of the British Standard. This improvement is related to the fact that date palm oil contains a high concentration of antioxidant isomers. The response surface methodology (RSM) technique was applied to optimise the conventional characteristics of bitumen at various palm oil clinker fine (POCF) concentrations and mixing conditions [61]. It was found that the addition of POCF increased the stiffness of bitumen by decreasing penetration values and increasing softening points and viscosity. The optimal condition was found at 7.75% POCF by weight of bitumen at a mixing temperature of 140 °C and a speed of 1000 rpm for 52 minutes. Another research on palm oil clinker (POC) was conducted by Babalghaith et al. [62] to evaluate the effects of POC as a fine aggregate on the mechanical properties of stone mastic asphalt. This time, POC was used in concentrations ranging from 0% to 100% of fine aggregates. With acceptable volumetric properties, Marshall stability, and flow, it was stated that the POC could completely replace the fine aggregate. Furthermore, POC-modified SMA demonstrated superior drain down, resilience modulus, and fatigue resistance compared to unmodified SMA.

Maleka et al. [63] investigated the effects of POFA as a filler on the indirect tensile strength of asphalt concrete. 5% POFA was used and stability, flow, stiffness, and indirect tensile strength of modified asphalt mixture were tested. In general, POFA improved the Marshall stability, flow, stiffness, and tensile strength of the asphalt mixture. That was attributed to the adequate mechanical properties of POFA that enhance the stiffness of the asphalt mixture and minimize the exposure to the distresses. POFA-modified asphalt mixture showed a 16% improvement in the tensile strength compared to the control asphalt mixture. The aforementioned findings are in agreement with the improvement of the mechanical properties, durability, and stiffness of the asphalt mixture that modified with 5% POFA was reported by

Maleka et al. [64]. The effects of POFA on the physical, aging, and rheological properties of asphalt binder were studied by Hainin et al. [65]. It was found that a decrease in penetration and increase in softening point of the modified binder were shown before and after the aging due to the addition of POFA, however, the temperature susceptibility increased, especially at the large amount of POFA. The aging index of viscosity reduced with increasing POFA, which reflects the reduction in the aging effects on the physical and rheological properties of binders that modified with POFA.

Yaro et. al. [66] evaluated the effects of short-term aging on the volumetric and mechanical properties of palm oil clinker fine (POCF) modified asphalt mixture. 4.9% POCF by weight of asphalt was used to prepare the modified asphalt. It was claimed that aged mixtures showed an improvement in the volumetric properties and Marshall stability compared to unaged mixtures. It was also stated that POCF-modified mixtures exhibited better mechanical performance compared to asphalt mixtures prepared with base asphalt before and after the short-term aging. The effects of POFA on the durability of dense-graded cold mix asphalt were evaluated by Usman et al. [67]. 3% POFA was used as a partial filler replacement and moisture damage and cantabro tests were conducted on the control and modified mixtures. It was found that addition POFA improved the volumetric properties, Marshall stability, adhesion properties, and moisture damage resistance. Such improvement was attributed to the POFA's pozzolanic capability that results in high tensile strength and adequate durability of POFA-modified mixtures. Table 2 summarizes most of the studies that reported in literature relevant to use the palm oil waste materials in asphalt binders and mixtures.

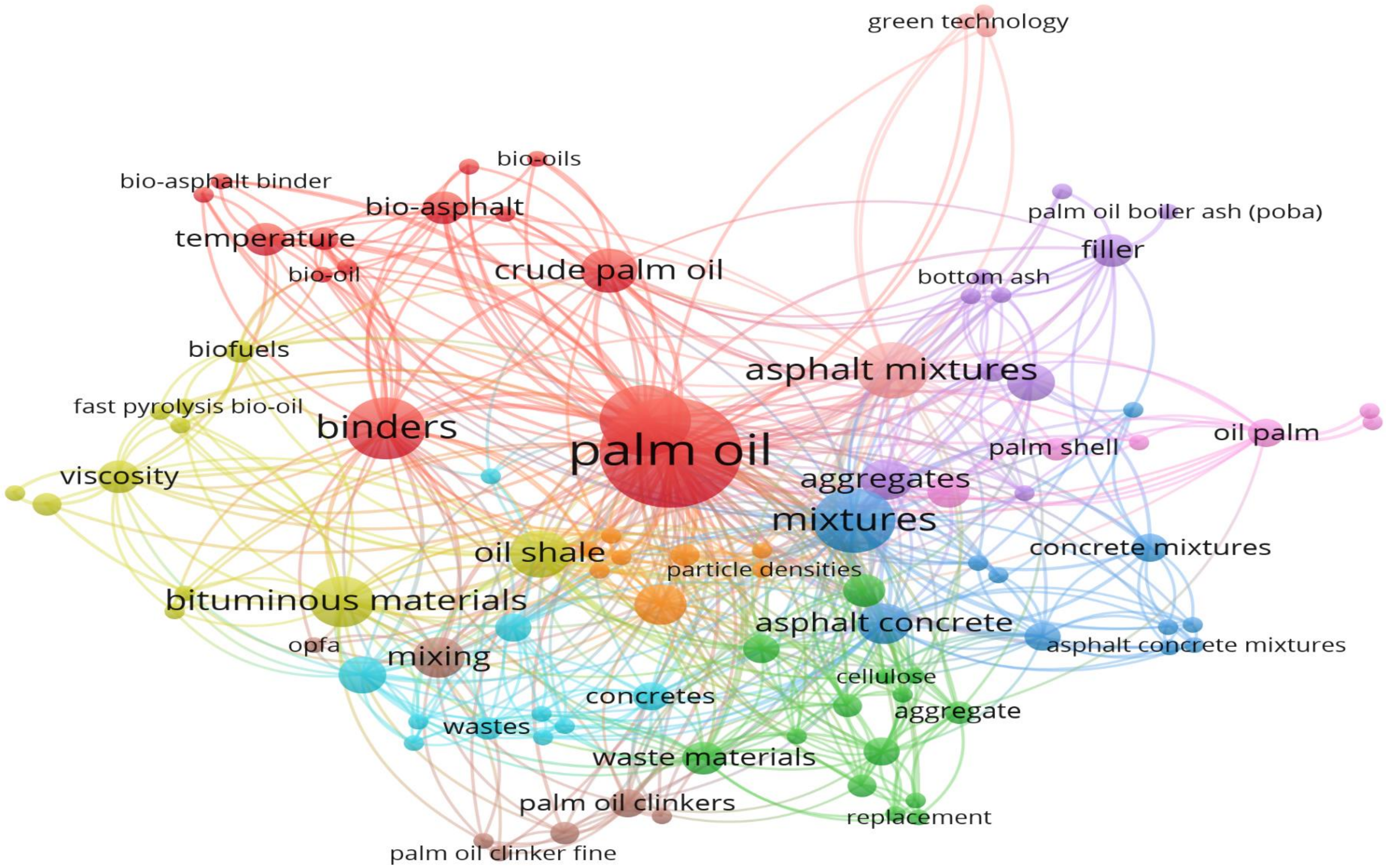

Fig. 12. VOSviewer mapping for palm oil and its by-products usage in asphalt pavement

Table 1. Summary of the findings from the literature on applications of palm oil in asphalt pavement

Reference	Objectives	Materials / Concentrations, wt%	Tests and Analysis Methods	Results and Findings	Remarks
Al-Sabaeei et al. [41]	To determine the rheological properties of bio-asphalt	CPO (0, 5, 10, and 15%) and asphalt PEN 60/70	Rolling thin film oven (RTFO), Dynamic shear rheometer (DSR), Artificial neural network (ANN)	- Higher CPO reduced complex modulus and increased phase angle - 5% CPO is the optimum - ANN is satisfactory for fast and accurate modeling	CPO showed promising bio-oil for bio-asphalt technology
Rafiq et al. [44]	To study the effects of CPO on the properties of CPO-modified RAP asphalt mixtures	CPO (8, 10 and 12%), RAP (0, 20, 40, 60, 80 and 100%) and asphalt PEN 60/70	Marshall stability and flow, Indirect tensile strength, RSM, FTIR, AFM	- CPO softened the RAP binders - 9.39% CPO showed the optimum to include up to 76% RAP - Aging properties f RAP improved due to CPO - CPO has enhanced the microstructural properties of base and RAP binders	CPO exhibited a significant improvement in restoring the aging properties of RAP binders and mixtures
Uchoa et al. [45]	To evaluate the effects of bio-based palm oil on the rheological and mechanical properties of asphalt	Hydrogenated palm oil fat (HPF) at 3%, Hydrogenated palm fat amide(FAA) at 3% and asphalt PEN 50/70	RTFO, FTIR, Thermo analysis of additives, Empirical and rotational viscosity, DSR, MSCR	- Mixing and compaction temperatures of binders were decreased due to HPF and FAA - HPF and FAA affect rheology as rejuvenators for aged asphalt - HPF and FAA showed significant changes in thermal and microstructural properties of asphalt	Bio-based palm oil is a significant bio-oil for the improvement of sustainable and renewable bio-asphalt, however, further investigation using a wide range of bio-oil was recommended
Al-Sabaeei et al. [48]	To assess the high-temperature rheological performance of rubberized bio-asphalt	CPO (0, 5, 10 and 15%), Tyre pyrolysis oil (TPO) (0, 5, 10 and 15%) and asphalt PEN 50/70	Consistency test, RTFO, PAV, DSR, MSCR, and RSM	- 5% CPO + 15% TPO showed the highest possible replacement to maintain PG 64 - 5% CPO + 5% TPO exhibited the optimum for high and intermediate temperature performances	Further studies were suggested to investigate the effects of CPO/TPO composite on the performance of asphalt mixtures such as WMA and SMA

				- CPO/TPO composite reduced the sensitivity of the binder for aging	
Alamawi et al. [46]	To investigate the performance, chemical, and thermal properties of bio-asphalt	Palm kernel oil polyol (PKO-p) (0, 20, 40, and 60%), diphenyl-methane diisocyanate (MDI) (30% by wt of PKO-p), and asphalt PEN 80/100	Physical tests, RTFO, Rotational viscosity (RV), thermal analysis, and FTIR	- Bio-asphalt binders showed 10% mixing and compaction temperatures lower than control. - Thermal resistance of bio-asphalt was similar to base asphalt with higher weight loss for bio-asphalt - Bio-oil introduce significant microstructural changes compared to base asphalt	PKO-p modified asphalt is a promising bio-asphalt for pavement applications. However, further performance evaluations are recommended.
Khairuddin et al. [47]	To study the physical and thermochemical properties of polyurethane (PU)/WMA additive composite asphalt binder and mixture	PKO-p (60%), MDI, PU (3%), Cecabase (0.5%), Rediset (0.6%) and asphalt PEN 60/70	Consistency tests, Storage stability, Thermal tests, Chemical analysis, RSM, Resielant modulus, and Dynamic creep	- Addition of PU improved the consistency, viscosity, stiffness, and rutting resistance of bio-asphalt due to the higher bonding strength and elasticity of PU-modified bio-asphalt - Cecabase and Rediset reduced the viscosity and mixing and compaction temperatures as well as enhanced fatigue performance - PU/Cecabase composite bio-asphalt mixture showed the highest resilient modulus and rutting resistance.	PU, Cecabase, and Rediset showed a limited effect on the thermal stability and microstructural of asphalt. Therefore more future optimization and investigation is recommended in this regards
Al-Sabaeei et al. [49]	To evaluate the physicochemical, rheological, and microstructural properties on nano-silica (NS) modified bio-asphalt	CPO (0, 5, 10 and 15%), NS (0, 2, 4 and 6%) and asphalt PEN 60/70	Physical tests, RTFO, DSR, MSCR, FESEM, and image processing analysis	- The viscosity of bio-asphalt was improved with NS particles. - Based on DSR and MSCR, NS-modified bio-asphalt exhibited significant improvement in rheological and aging properties and 5% CPO and 4% NS showed the best performance - FTIR and FESEM results supported the physical and rheological findings	The low-temperature performance of NS-modified bio asphalt was recommended to be evaluated at the regions where the low-temperature failure is the main concern

Table 2. Summary of the findings from the literature on applications of palm oil by-products in asphalt pavement

Reference	Objectives	Materials / Concentrations, wt%	Tests and Analysis Methods	Results and Findings	Remarks
Borhan et al. [50]	To study the effects of POFA as a filler on the mechanical properties of asphalt mixtures	POFA (0, 1, 3, 5, and 7%), granite aggregate, and asphalt PEN 80/100	Marshall stability, resilient modulus, static creep, dynamic creep, and fatigue test	- POFA improved stability, elasticity, stiffness, and resilient modulus of asphalt mixtures - The creep resistance of asphalt mixture enhanced due to the pozzolanic cementing properties of POFA - Fatigue life of modified mixtures improved due to the enhancement of the elastic recovery - 5% POFA showed the optimal performance	The incorporation of POFA higher than 5% with maintain desired performance is suggested to be further studied
Yaro et al. [52]	To evaluate the impact of mixing processes on the performance of waste palm oil fiber (WPOF) modified SMA	WPOF (0, 0.15, 0.3, 0.45, and 0.6% by weight of total mix), crushed granite, asphalt PEN 60/70, and ordinary Portland cement as a filler	Drain down, adhesion test, moisture damage test, Cantabro test, stiffness modulus test, traditional mixing process, and sequential mixing process	- Optimum bitumen content of mixes with sequential process lower than traditional by 0.94% - WPOF and sequential process results in the lower drain down, higher stability, tensile strength, and stiffness of mixes - Moisture damage resistance met the requirements for both mixing processes - Optimal WPOF was found at 0.3%	- It was stated that no significant effect was shown for sequential process on moisture damage resistance - There are limitations for such study, for example, the materials cost, long time of mixing. Therefore life cycle cost analysis on the use of the sequential process is recommended for future research
Rosyidi et al. [68]	To assess the physical, chemical, and thermal properties of asphalt binder modified with palm oil boiler ash (POBA) and WMA additive	POBA (3%, 5%, 7% and 9%), 2% Rediset as WMA additive and PEN 60/70	Penetration, softening point, ductility, rotational viscosity, FTIR, SEM, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA)	-7% POFA showed the enhancement of consistency properties of WMA-modified asphalt -It was reported that no chemical interaction was found among the molecular of POBA in the WMA modified asphalt matrix -There were no significant changes in the physicochemical transitions due to the addition of POBA	An extensive study on the surface energy and adhesion properties and morphological characteristics of POBA modified binders were recommended

Kargari et al. [69]	To optimize the use of palm oil capsules on the self-healing technique of unaged and aged asphalt mixtures	Nine types of calcium alginate capsules with various oil to water ratios, percentages of palm oil capsules in mixtures (0, 0.035, and 0.7% by total weight of the mixture)	Indirect tensile stiffness modulus (ITSM), semicircular bending test (SCB), self-healing with resting periods, and microwave healing	-Using palm oil capsules significantly improved the self-healing of aged and unaged asphalt mixtures -Microwave healing promoted a healing speed of asphalt mixture at unaged and aged conditions -Palm oil capsules slightly reduced the stiffness modulus of mixtures due to the release of oil from capsules into asphalt mixture during the mixing and compaction process	Palm oil capsules exhibited a significant increase in the healing properties of asphalt mixtures with a slight effect on the stiffness. Therefore, further investigation to mitigate the effects on the mechanical properties is recommended
Babalghaith et al. [16]	To investigate the mechanical performance of SMA with POC as a fine aggregate substitution	POC (as a fine aggregate), POFA (as a filler), crushed granite, and asphalt PEN 60/70	Resilient modulus, wheel tracking test, dynamic creep test, indirect tensile strength, and cantabro durability test	- Using 50% POFA as a filler enhanced the mechanical properties compared to control - Modified SMA improved the resilient modulus, rutting resistance, durability, and moisture damage resistance of the control mixture - Optimal POC was found between 40% and 60% for the best mechanical properties.	Using POC is feasible for highway applications to mitigate the environmental issues due to disposal of POC and to enhance the performance of asphalt pavement
Rusbintardjo et al. [56]	To assess the physical and rheological properties of oil palm fuel ash (OPFA) modified asphalt	OPFA (2.5, 5, 7.5, 10,12.5 and 15%) and asphalt PEN 80/100	Consistency tests, temperature susceptibility, storage stability, viscosity, RTFO, PAV, DSR, BBR, and DDT	- OPFA improved the consistency and temperature sensitivity resistance of base asphalt however storage stability negatively affected - OPFA-modified asphalt can resist rutting, fatigue and low temperature cracking up to 70, 20, and -15 °C, respectively - 5% fine OPFA found to be the optimal	It was stated that it is feasible to use OPFA as an asphalt modifier
Usman et al. [59]	To study the effect of POFA on the mechanical properties of cold dense -graded asphalt mixture	POFA (1, 2, 3, and 4%), Portland cement (as a filler), granite aggregate, emulsion	Marshall stability and flow, indirect tensile stiffness modulus, dynamic creep test, moisture susceptibility test, cantabro test,	- POFA modified mixtures showed lower stability compared to the control mixture, however, modified exhibited better moisture damage resistance - POFA enhanced the stiffness, durability, and rutting resistance of cold asphalt mixtures - 3% POFA was recommended as optimal to satisfy most of the performance requirements	It was reported that some of the trade-offs among the different properties of the modified cold mixture, therefore, further studies to overcome such trade-off is suggested

Zulkefli et al. [70]	To evaluate the effects of different sizes of POFA on the physical properties of asphalt	POFA (0, 5, and 7%) grounded at 1 and 4 hours and PEN 80/100	Transmission electron microscopy (TEM), storage stability, penetration, softening point, and temperature susceptibility	- Adding POFA into base asphalt at different sizes and percentages significantly reduce penetration and increase softening point -Binder modified with 7% and particles size of (500 nm to 3µm) showed the best properties among all tested binders -All modified binders exhibited temperature sensitivity lower than base asphalt before and after aging	Investigating the effects of POFA sizes on the advanced rheological, chemical and microstructural properties of asphalt is an interesting aspect for future research
Usman et al. [71]	To propose a performance-based mix design for cold mix asphalt (CMA) modified with POFA	POFA (1-4%), Granite aggregate and filler, and emulsifier asphalt	Indirect tensile stiffness modulus (ITSM), Cantabro, and indirect tensile strength (ITS) tests	-Proposed design procedures based on ITSM and ITS was established -There is a significant correlation between the proposed design and Marshall design at optimum emulsion content -3% POFA was found to be the optimum to improve the moisture resistance and enhance the volumetric, mechanical, and marshall properties of CMA	Developing an international CMA design procedure is a research gap that needs extensive efforts from researchers, governments, and industries.
Yaro et al. [61]	To model and optimize the mixing parameters of POC-modified asphalt binders	Palm oil clinker fine (POCF) (2, 4, 6, 8, and 10%) and asphalt PEN 60/70	Microstructural characteristics, physical properties, RSM, storage stability FTIR, SEM and EDX	- POCF improved the consistency and stability of asphalt binder - RSM optimization showed that 140 °C, 1000 rpm, and 51.9 minutes are the optimal temperature, speed, and time, respectively of mixing POCF into base asphalt - Microstructural analysis showed a good dispersion of POCF in asphalt matrix	Further and advanced rheological and performance evaluations are recommended
Syammaun and Rani [72]	To evaluate the effects of oil palm fiber (OPF) on the resilient modulus of porous asphalt mixture	OPF (1%, 2%, 3%, 4% and 5%), PEN 80/100 and crushed granite aggregate	Indirect tensile stiffness modulus (ITSM)	-Addition of OPF showed significant enhancement of ITSM of porous asphalt up to 3% -Effects of binder contents on the ITSM was not consistent which indicated the non-linear damage process of specimens	Evaluating the durability, rutting, fatigue and other performance of OPF-modified porous asphalt is a research gap to come up with a comprehensive idea on the behavior of OPF in porous asphalt

Aziz et al. [73]	To assess the effects of cellulose oil palm fiber (COPF) on the physical and rheological properties of asphalt binder	COPF (0.2, 0.4, 0.6, 0.8 and %) by weight of asphalt and PEN 60/70,	Penetration, softening point, viscosity, short term aging, long term aging, and dynamic shear rheometer (DSR) tests	-The COPF modified asphalt showed a decrease of penetration and an increase of softening point and stiffness with the increase of COPF -Significant improvement was shown in the complex modulus, rutting, and fatigue parameters of modified binders compared to base asphalt due to the improvement of modified binders' elasticity	It was stated that COPF-modified binders have a high potential to resist rutting and fatigue distresses at high and intermediate temperatures
Babalghaith et al. [62]	To study the effect of palm oil clinker on the mechanical properties of SMA	POC (0, 20, 40, 60, 80, and 100%) as a fine aggregate replacement, POFA as a filler, crushed granite aggregate, and asphalt PEN 80/100	Marshall stability and flow, drain down, resilient modulus, and indirect tensile fatigue test	- POC has no significant effect on marshall stability and flow - With an increase of POC, drain down decreased and stiffness increased - PCO improved the elastic and fatigue life of SMA - Overall, 100% POC replacement of fine aggregate satisfy all mixed design requirements	Green, sustainable, and environmental friendly SMA mixtures can be developed by incorporating POC as a fine aggregate replacement

6. Motivations and challenges for using palm oil in asphalt pavement as bio-binder

Researchers and bitumen industries are looking for innovative ways to improve the performance of asphalt road pavements and reduce their carbon footprint, particularly in recent years as demand for bitumen in pavement construction increased despite the limited, unstable, and fluctuating price of petroleum [74, 75]. Continuously increasing traffic loads result in pavement failures, requiring sustainable design, construction, and material selection for pavement. Biomaterials are a growing area of interest in pavement engineering due to their renewable resources, low cost due to local production, environmental friendliness, and lower energy usage when compared to petroleum-based materials [76-82]. Numerous attempts have been made to develop biomaterials that can be used as modifiers, extenders, or replacements for asphalt binders. Overall, these approaches successfully used bio-binders as extenders to a limited extent. Looking into the details of these biomaterials, we can see very limited studies that used CPO in bio-asphalt binders research. CPO is readily accessible and less expensive than other oils for the same function. CPO can therefore be used in significant amounts in pavement-related applications in the future, such as bio-asphalt binders.

After Indonesia, Malaysia has the second-largest reserve and supply of palm oil. Importing bitumen from outside Malaysia or even treating waste cooking oil (WCO) to be used as a bio-binder is more environmentally cost-effective than using paralysis [5]. At room temperature, palm oil is in a semi-solid state, and this characteristic makes it an excellent candidate for use as a bio-binder. This trait is also one of the driving forces behind the use of palm oil as a bio-binder, as it can potentially contribute to the resolution of the viscosity problem caused by the addition of bio-oil to bitumen. Palm oil has a high level of oxidation resistance when exposed to high temperatures [5]. Furthermore, CPO extraction is carried out at temperatures ranging from 90 °C to 140 °C [3], suggesting that CPO does not age like WCO. This feature is one of the justifications for adopting palm oil as a bio-binder to help solve the global problem of bio-binder aging. Table 3 shows some of the physicochemical properties of CPO and its components.

Although oil palm waste materials are abundant, their high water and oxygen concentration precludes and limits their utilization as bio-oils in bitumen. On the other hand, CPO has lower water content and higher resistance to oxidation [12]. The following points summarise the benefits of utilising palm oil as a feedstock for the production of biofuel and bio-binders [15]:

- Palm oil is made of sustainable and renewable materials compared with fossil fuels. It can be sustained by re-planting palm seeds to restore palm plantations.
- Palm oil has higher oxidation stability than other bio-diesel feedstock, such as Jatropha oil, making it more suited for use as a bio-binder, as aging is one of the challenges with bio-binders.
- When compared to fossil fuel products, palm oil is safer to handle (biodegradable).
- Substantial revenue is generated from the decrease of bitumen imports as well as the export of palm oil products such as biodiesel.
- Palm oil is an environmentally friendly resource that has the ability to contribute to global warming mitigation.

Table 3. Physicochemical properties of CPO and its components [83]

Characteristic	**Value**
Appearance	Deep orange-red
Density (40 °C)	0.899–0.920
Softening point (°C)	33–40
Refractive index (50 °C)	1.449–1.455
Acid value (mg KOH/g oil)	2–15
Typical solid fat content (40 °C)	1–6%
Carotene content	0.03–0.15%
Iodine value	50.0–55.0
Saponification value (mg KOH/g oil)	190–209

The primary challenges associated with using CPO in asphalt pavement applications are securing palm oil as a feedstock for non-food products such as biofuel and bio-asphalt, as well as securing a sufficiently large amount of palm oil as edible oil to ensure food and energy security, particularly in light of the expectation that fossil fuels will run out in 50 years. Competition between the biofuel and food industries should be avoided since this will lead to increased consumer needs, which in turn will cause increased demands for vegetable oil and the increased price of palm oil [15].

7. Application of palm oil and its by-products in building construction

Shells and fibres are the primary solid wastes generated by the palm oil industries. As shown in Fig. 13, these two materials are subsequently burnt to produce ashes and clinkers known as palm oil fuel ash (POFA) and palm oil clinker (POC).

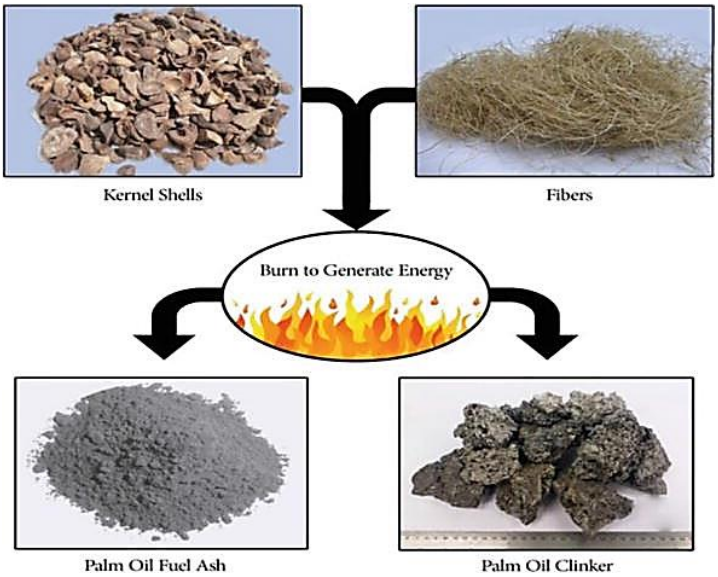

Fig. 13. Production of POFA and POC [84]

In accordance with the studies indexed in the Scopus database and visualized by VOSviewer, it can be seen that most of the studies used POFA as partial cement replacement, supplementary cementitious material, geopolymer binder, alkaline activated binder, and pozzolanic material. The majority of its application is in concrete, geopolymer, lightweight foamed concrete, and a little usage in masonry block. A few studies have used POFA for soil stabilization as shown in Fig. 15. On the other hand, POC is mostly used to generate lightweight concrete and infrequently used for producing geopolymer, previous concrete, sustainable concrete, self-compacting mortar, and masonry grout as shown in Fig. 16.

A new review [9] was conducted to assess researchers' efforts to use ~~palm oil fuel ash~~ POFA as a partial substitute for concrete production. Numerous studies in the review established that POFA-modified concrete outperforms untreated concrete in terms of durability and compressive strength. When compared to concrete made entirely of ordinary Portland cement (OPC), POFA reduces CO_2 emissions and improves environmental conditions. Another significant aspect brought in the analysis is that POFA contains around 50% to 70% silica by weight. According to the review's author, composite nano-silica/POFA-modified concrete increases the compressive strength and durability of concrete by 15% when compared to control concrete.

The feasibility of using POFA as a partial OPC replacement for concrete has gripped the attention of many researchers worldwide. Several researchers have investigated self-compacting concrete (SCC)'s fresh and hardened characteristics, including POFA as cementitious materials [85-89]. The outcome of the studies has indicated that the strength of SCC increases with increased POFA contents. Furthermore, SCC made with POFA has been demonstrated to be more resistant to sulphate and chloride attack, resulting in increased durability. In recent years, research has been conducted on the production of sustainable geopolymer binders utilizing industrial waste, such as POFA [90-92]. The effect of POFA in geopolymer concrete is shown in Fig. 14. The results revealed that a denser and more homogeneous geopolymer mixture is formed during the curing process, resulting in improved compressive strength. However, microcrack propagation in the interfacial transition zone (ITZ) is a common cause of concrete deterioration.

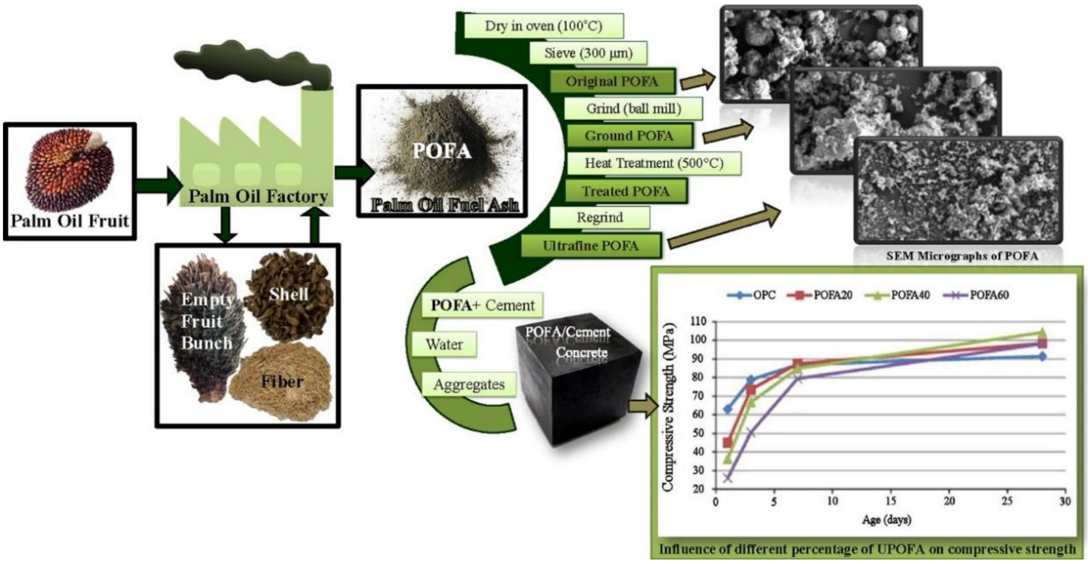

Fig. 14. Development of geopolymer concrete incorporated POFA [93]

Even though POFA is a pozzolanic material that is extensively used to increase the strength and durability of concrete, there has only been a little literature that investigated its usage in the manufacturing of burnt clay bricks. The incorporation of 1–10% palm oil wastes (POFA, palm kernel shells, fibres, and POC) resulted in a reduction in the strength and durability of the clay bricks but produced lightweight clay bricks with a lower thermal conductivity [94-97]. POC is commonly used as a lightweight aggregate due to its low weight. In addition, river sand and broken granite stone claimed to be 25% and 48% heavier than POC, respectively; furthermore, mortar containing 100% POC sand has a 7% lower density than river sand [98-101].

Following 1984, many studies were conducted to determine the feasibility of using oil palm kernel shell OPKS as a lightweight aggregate in concrete. The review established that OPKS-concrete has comparable structural behaviour and mechanical properties to normal-weight concrete. Moreover, according to a recent study, OPKS-concrete can be utilised to make medium- and high-strength concrete [4]. Another recent study found that partially substituting oil palm boiler clinker (OPBC) for aggregates in lightweight concrete can increase the compressive strength by approximately 40%.

The feasibility of utilizing POFA as a partial OPC replacement for concrete has gripped the attention of many researchers worldwide. A recent study investigated the compressive strength and impacts of nano palm oil fuel ash (nPOFA) as a cementitious material. The research found that when nPOFA increases, compressive strength rises by up to 40% and based on the study, nPOFA can be utilized as an eco-friendly cementitious material [102]. Further studies have revealed that the partial replacement of OPC by 10 to 50% POFA has resulted in a strong reduction of concrete by 20 to 50%, however, the sulfate attack was significantly reduced [103]. Moreover, the nano nPOFA has improved the strength properties of concrete compared to normal POFA. This enhancement can be attributed to its fineness and its low carbon content [104, 105]. Hamada et al. [106] investigated the properties of lightweight concrete incorporating nPOFA (ranged between 0 – 30%) and found that the highest compressive strength (58.3 MPa) was achieved for the mix having 30% cement replacement by nPOFA, while the mix with 10% nPOFA exhibited the lowest compressive strength (40.7 MPa). In general, it is concluded that nPOFA has a considerable impact on concrete, especially at later ages, in terms of enhancing workability and compressive strength. On the other hand, POFA has low pozzolanic activity in the concrete matrix which resulted in a reduction in compressive strength at the early age of curing [107]. The study exhibited that concrete having 60 – 20% nPOFA revealed up to 84% reduction in chloride penetration compared to normal concrete [104].

Tangchirapat et al. [108] studied the compressive strength, expansion due to sulfate attack, and initial and final setting time for concrete containing POFA and found that the setting time for POFA concrete was delayed and was governed by the POFA content in the concrete mix and its fineness. The heat of concrete containing POFA was also examined, and it was discovered that concrete hydration heat is mostly determined by chemical material interactions [109]. Moreover, concrete having POFA as a replacement of cement possessed a better resistance to harsh environments than ordinary concrete [110]. The fineness of POFA concrete can be increased by employing pozzolanic material, which forms more C–S–H gels when Al_2O_3 and SiO_2 contact with $Ca(OH)_2$, boosting sulfate resistance and lowering $Ca(OH)_2$

concentration [111]. This reaction results in a denser microstructure and the formation of extra C–S–H bonding, which reduces concrete porosity and permeability. Additionally, the POFA fineness enhanced the interfacial bond, resulting in improved concrete strength, transport properties, and durability as a result of its micro-filling capability and pozzolanic reactivity [112].

Studies revealed that with the increase of POFA content in concrete, the water permeability decreases with increasing age attributed to the formation of additional gel during the pozzolanic reaction of ash [109, 113, 114]. Overall, it can be concluded that POFA enhanced the impenetrability of concretes by reducing porosity and improving pore refinement. Similarly, the water absorption in concrete is enhanced with an increase in POFA content, because high POFA content could contribute to the formation of a more porous concrete matrix [115]. Furthermore, POFA concrete has greater resistance to sulfate and acid attacks than normal concrete because POFA has an alternative low-toxicity coating as well as due to its fineness [116, 117]. Ting et al. [118] concluded that POFA becomes extremely pozzolanic (rich in SiO_2) and has better concrete characteristics in both fresh and hardened states when appropriate treatment techniques are used. The main findings from some recent literature on applications of palm oil by-products in concrete mixtures are summarized in Table 4.

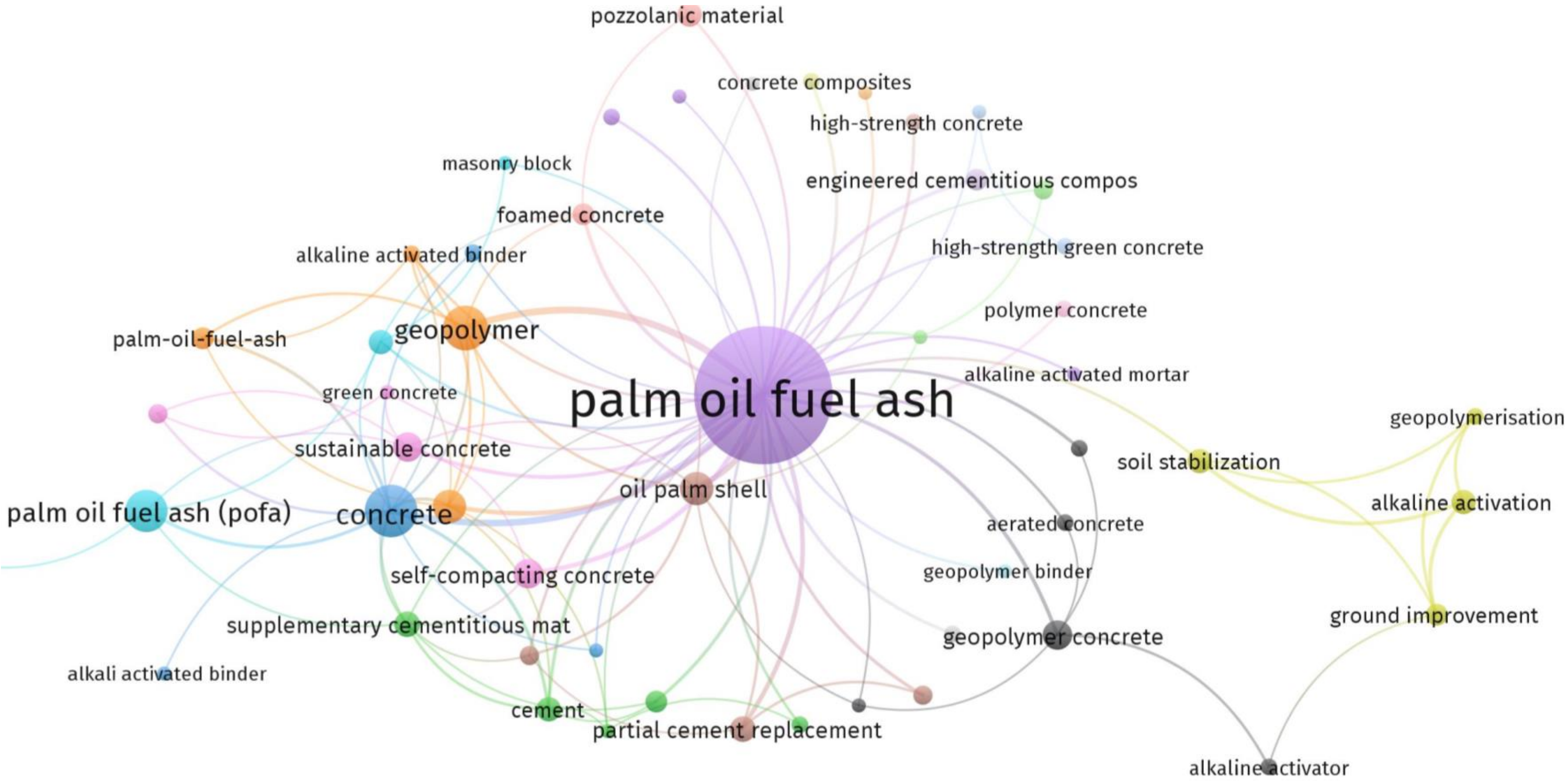

Fig. 15. VOSviewer mapping for POFA usage and applications

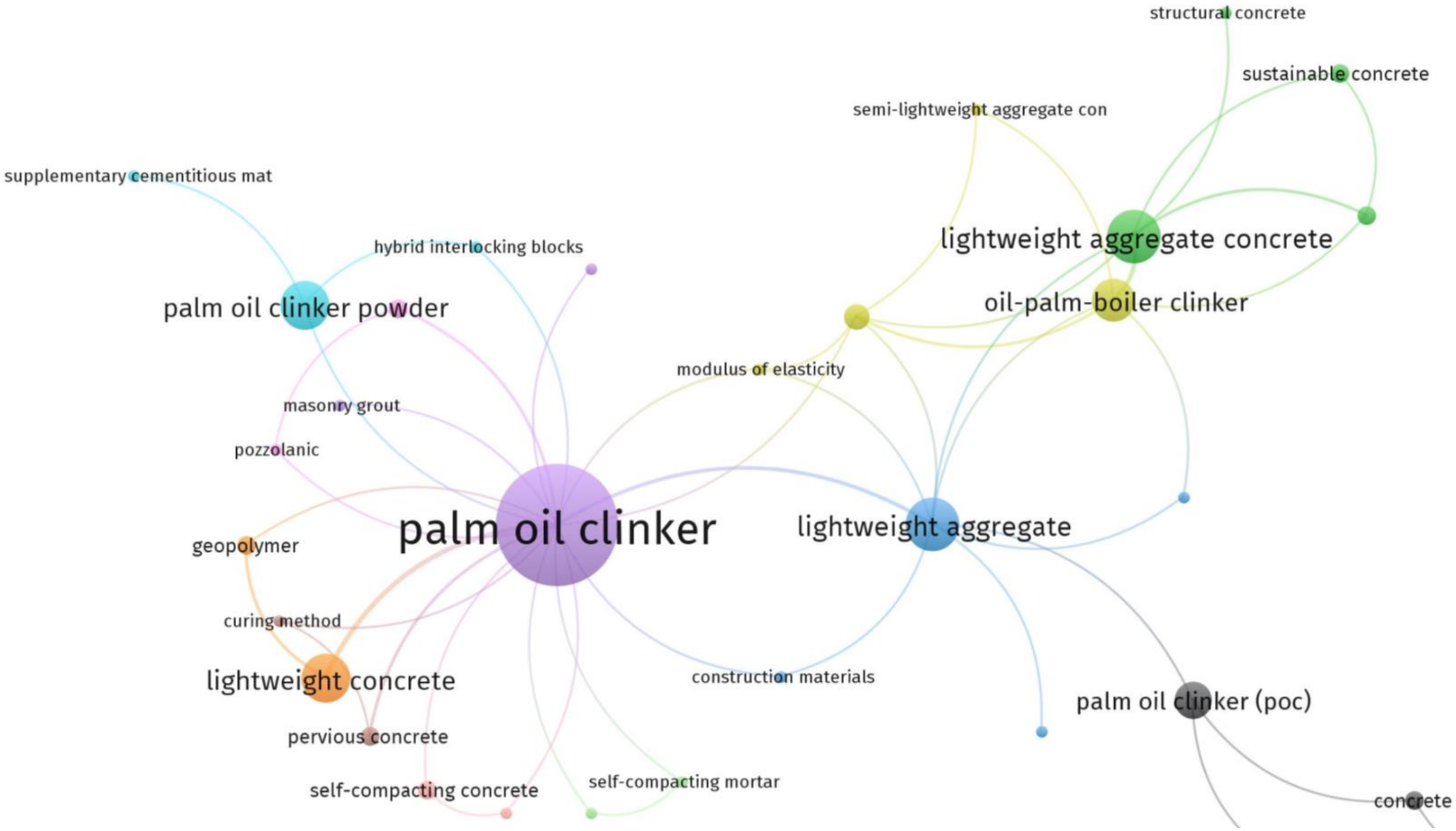

Fig. 16. VOSviewer mapping for POC usage and application

Table 4. Summary of the findings from some recent literature on applications of palm oil by-products in concrete mixtures

Reference	Objectives	Materials / Concentrations , wt%	Tests and Analysis Methods	Important findings	Remarks
Amin et al. [119]	Using NCSA and PLA as partial replacement to cement in ultralight-performance concrete (UHPC)	Nano cotton Stalk Ash (NCSA):0%, 2.5%,5%,7.5%, Palm leaf ash (PLA): 10%, 20%,30%	scanning electron microscopy, thermogravimetric analysis with differential thermal analysis and X-ray diffraction, Compressive strength, Splitting tensile strength, Flexural strength, Modulus of elasticity,	- The addition of NCSA and PLA reduces the slump flow. - Up to 20% of PLA and 5% of NCSA by mass of cement increased the compressive strength by almost 17%. - Replacement of up to 40% of NCSA and PLA as replacement of cement in concrete is possible.	The ash's characteristics were improved by heat treatment, which removed carbon and unburned organic materials while causing a minor change in the mineral composition of the PLA.
Hamada et al. [120]	To increase the strength of semi-light weight aggregate concrete by partially replacing the cement with NPOCP and the coarse aggregate with POC.	Nano-palm oil clinker powder (NPOCP): 0%, 10%, 20%, 30%, and 40%. Palm oil clinker (POC): As coarse aggregate	Chemical composition of binder materials, Density of Concrete, Compressive strength	- NPOCP shows a huge amount of SiO2 of up to 63%. - As the NPOCP increased in the mix, the density of semi-LWAC decreased. - 7-days compressive strength of the control mix was highest among the mixtures but the addition of 10% NPOCP showed the highest compressive strength after 28 days.	In semi-lightweight aggregate concrete (semi-LWAC), adding NPOCP promotes workability. Density falls as NPOCP is added to the concrete mix.

Muthusamy et al. [121],	To study the effect of coal bottom ash (CBA) content as partial sand replacement on workability and compressive strength of palm oil clinker lightweight concrete.	coal bottom ash (CBA): 0%, 10%, 20%, 30%, 40%. Palm oil Clinker (POC): as Coarse aggregate	Workability (Slump testing), compressive strength, scanning electron microscopy, water absorption,	- CBA showed to have up to 34.7% SiO2. - Mix produced using 10% CBA of slump 70 mm is deemed suitable for a reinforced concrete application. - Increase in CBA reduces compressive strength however, the addition of up 10% of CBA forms a more environmentally friendly concrete with compressive strength closer to the control specimen. - water absorption increases with the increase in CBA and the addition of up to 40% of CBA had lower than 3% water absorption.	Concrete with 10% CBA had the desired strength. Excessive usage of CBA at 40% reduces strength and should be avoided.
Mohammadhosseini et al. [122]	To investigate one-year creep and drying shrinkage performance in addition to the strength development of concrete comprising waste polypropylene carpet fibre and (POFA.	POFA; 20% PP fibers: 0 – 1.25%	One year creep, drying shrinkage, and compressive strength	- The mixture of carpet fibers with POFA increased concrete's long-term compressive strength (ranged 43–54 MPa) while reducing creep strain and drying shrinkage by around 15% and 27%, respectively.	The use of industrial waste carpet fibers in conjunction with POFA in the creation of green concrete as structural components has a bright future.

Tasnim et al. [123]	To study the effect of using POFA on the durability of cement paste in ammonium nitrate solution	10 µm POFA up to 30% replacement treated at 20% concentration of ammonium nitrate solution for 90days.	Durability properties including sorptivity, the volume of permeable voids (VPV), thermo-gravimetric analysis (TGA) at 28, 56, and 90 days.	- Cement paste containing 10% and 20% fine POFA exhibited the lowest sorptivity value at 56 and 90 days in ammonium nitrate solution while POVA at 30% shows higher VPV. - POFA shows lower $Ca(OH)_2$ content with a corresponding increase in the percentage of POFA replacement.	T0he optimal mixture was accomplished for the mix having 20% of 10 µm POFA for better resistance against ammonium nitrate solution at 90 days.
Alnahhal et al. [124]	To evaluate the performance of using palm oil fuel ash (POFA), as a cement replacement material to produce cellular lightweight foamed concrete	Palm oil fuel ash (POFA): 10%, 20%, and 30%	compressive strength, splitting tensile strength, water absorption, porosity, sorptivity, X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray (EDX), ultrasonic pulse velocity and electrical resistivity	- Partial replacement of POFA in foam concrete showed a 43% reduction in density due to permeable foams and makes it suitable for non-structure concrete. - 20% of POFA recommended as replacing 30% of OPC by POFA reduced the strength. - SEM images showed micro-cracks when 30% POFA was used in foamed concrete. - Among foamed mixes,20% POFA replacement had the lowest sorptivity. A slight reduction in the peaks of various crystalline phases was observed in the XRD results.	

Mujedu et al. [112]	To determine the impact of elevated temperatures on the microstructure and compressive strength of SCC (Self-compacting concrete).	POFA (Palm oil fuel ash):15% replacement by weight of cement.	A) The samples were subjected to 200 to 1000 °C temperature. B) compressive strength of SCC samples, scanning electron microscopy, X-ray diffraction analysis	- The compressive strength of POFA-SCC was improved after 28 days. - Rapid Loss of mass was observed with the increase in temperature from 200 and 400 °However, the loss of from 600 to 1000 °C had a slow rate. - Both POFA-SCC and OPC-SCC's residual compressive reduced from temperatures 27 to 200°C and increased at 400 °C and reduced continuously for the temperatures above 400 °C. - Crystalline CH and C-S-H were observed in SEM results after 28 days for POFA-SCC and OPC-SCC. Meanwhile, no pores and micro-cracks were seen on both POFA-SCC and OPC-SCC.	POFA can partially replace OPC in SCC fabrication, improving its strength at low and high temperatures, especially at 400 C. However, it is not suggested above for temperatures 600 °C due to energy efficiency and strength loss.
Alaskar et al. [125]	To enhance the abrasion and skid resistance of concrete as a pavement material by reinforcement with polypropylene (PP) fibers.	PP (polypropylene) fibers: 0%, 0.25%, 0.5%, 0.75%, 1%, and 1.25%. 12 samples with OPC: 100%. 6 samples with 20% POFA and 80% OPC.	tensile and compressive strengths, modulus of elasticity, abrasion resistance, skid resistance, Scanning electron microscopy, statistical analysis.	- Compressive strength of both concrete mixtures modified with PP fibers was reduced. However, POFA modified mixtures showed higher compressive strength. - Tensile strength of all mixtures increased and the addition of 0.75% of POFA increased the tensile strength by 30%. - addition of 1% of PP fibers increased the abrasion resistance in the mixtures by 25%. - Strong correlation between skid resistance and abrasion for the concrete pavement was found for all fiber volumes.	The combination of PP fibers and POFA in the mixtures was beneficial to some extent for use as concrete pavement.

Rajesh et al. [126]	To study the strength properties of POFA concrete	10, 20, and 30% substitution into the concrete by POFA.	Compressing quality, flexural quality, and split rigidity test.	- the strength of concrete increased with increasing POFA content up to 20%. - POFA reduces drying shrinkage as fine as the workability of concrete.	the most extreme quality was attained at 20% of supplanting concrete with POFA.
Hamada et al. [106]	To examine the feasibility of developing green concrete incorporating nPOFA and nano eggshell powder (ESP) as cement replacement on concrete.	nPOFA at ratios of 0, 10, 20, and 30%. And ESP proportions constituted 2.5% and 5% of the total binders.	Compressive strength, ultrasonic pulse velocity, and water absorption,	- nPOFA exhibited a significant improvement in the strength of developed green concrete, especially at replacement levels of 10% and 20% of cement with nPOFA contents. - ESP improved concrete durability by reducing water absorption. - nPOFA reduced the concrete density due to the low weight and specific gravity of nPOFA and NESP.	The developed green concrete may have high resistance to environmental attacks such as sulfates and acids attacks.
Chindaprasirt et al. [127]	To study the amount of water permeability and strength of concrete incorporating POFA	20%, 40%, and 55% by weight of the binder	Water permeability and compressive strength	- POFA resulted in higher water demand in concrete mixtures as compared to ordinary concrete with compatible workability. - The compressive strengths of concretes containing 20% of POFA were higher than of ordinary concrete and were reduced with the increase in the replacement ratios.	It is concluded that POFA can be applied as new pozzolanic materials to concrete with an acceptable strength as well as permeability.

Jhatial et al. [128]	To use finite element simulation to examine the performance of eco-friendly lightweight foamed concrete including two waste products, Eggshell Powder (ESP) and Palm Oil Fuel Ash (POFA), comparing the simulated findings with experimental data.	POFA (Palm oil fuel ash):20% to 35% ESP (Eggshell powder):5% to 15%	The Modulus of Elasticity and Poisson's ratio toughness, Surface temperature measuring, Abaqus modeling	The temperature on the surface of the eco-friendly lightweight concrete panels dropped with thickness. The simulated results with ABAQUS were within an acceptable range of 10%, which could be reduced to 2% of all panels that had a fixed thickness of 50 mm. In this way, a computational model could effectively analyze the thermal performance of eco-friendly lightweight concrete made from waste resources.	computational modeling can predict thermal stresses and heat transfer for eco-friendly lightweight concrete and provide fast track thermal performance analysis of eco-friendly lightweight concrete incorporating various waste materials.
Chalee et al. [129]	To enhance the durability of concrete at a marine site by using ground palm oil fuel ash (GPOFA) after subjecting to tidal zone conditions for 7 years.	A) Ground palm oil fuel ash (GPOFA): 0%, 15%, 25%, 35%, and 50% as substiture for OPC. B) W/C (Water to cement) ratio varied from 0.4 to 0.5. C) concrete samples sizes of 200*200*200 mm3 with 3 embedded streels at distances of 20, 50, and 75 mm to the sides of the samples.	Compressive strength, Chloride penetration, Chloride-binding capacity, Corrosion of embedded reinforcing steel bars, EDS (Energy Dispersive X-Ray Spectroscopy) analysis.	- Concrete mixtures containing 15-35 percent GPOFA had stronger compressive strength than other mixtures after 7 years of exposure to seawater. - The chloride intrusion in concrete decreased as GPOFA increased up to 35% of cement weight. - The chloride binding capacity improves with GPOFA content up to 25% of cement weight and decreases with GPOFA content of over 35%. - Addition of up to 35% of GPOFA, reduced the corroded area of steel bars.	Based on the results, the concretes containing GPOFA at replacement levels of 15-35% of binder weight, and having a W/B ratio of 0.45 or less, are recommended for concrete used in marine sites because they provide good durability performance

Abduljabbar et al. [130]	To investigate the physical and mechanical properties of green concrete comprising polypropylene carpet fiber waste and palm oil fuel ash (POFA)	A) OPC modified with 20 mm multi-filament polypropylene (PP) carpet fiber: 0%, 0.25%, 0.5%, 0.75%, 1%, and 1.25%. B) POFA modified with 20 mm multi-filament polypropylene (PP) carpet fiber: 0%, 0.25%, 0.5%, 0.75%, 1%, and 1.25%.	Workability (Slump test), Compressive strength, Spitting tensile strength, Flexural strength of prismatic beams, Drying shrinkage.	- The workability was reduced by introducing carpet fiber to the mixtures and slump values decreased. - The increase in fiber content, reduced the compressive strength of all the mixtures. - During the 7 and 28 days curing period, the compressive strength of OPFA modified mixtures with fiber reduced compared to that of OPC mixtures and increased afterward, which is due to the pozzolanic activity of POFA modified mixtures. - Fiber-cement-matrix interface caused increased values of flexural and tensile strength of POFA modified mixtures with fiber. - Drying shrinkage was reduced with the addition of carpet fibers to the POFA and OPC mixtures.	The outcomes of this study showed that there is a promising future for the consumption of industrial carpet fibers waste together with POFA in the production of green concrete as structural components.
Suamy Nadh et al. [131]	To examine the behavior of bond and durability properties of treated oil palm shells as coarse aggregates.	Oil palm shells (OPS): 25% of coarse aggregate sized 10 m with porosity of 29.8%	mechanical (Bond between the reinforcement and binder known as pull out test) and durability(Permeability, and sulfate attack) behavior.	- OPS coating reduced the water absorption from 25% to 8% and increased desirable aggregate impact value. - Compressive strength and bonding between aggregate and matrix increased when TOPS was used as coarse aggregate. - Alkali-silicate reaction is below 0.2% - Density reduced by 28% when used TOPS as coarse aggregate.	TOPS are better alternate material for the replacement of coarse aggregate in concrete

8. Motivations and challenges for using palm oil by-products in concrete materials

The main motivation behind using waste materials in the construction industry is to reduce the increasing amount of harmful industrial and agricultural wastes. Like other industrial and agricultural wastes, palm oil direct by-products such as palm oil shells and fruit bunches are hard to recycle and should be thrown away to landfills if not used by other industries that create an environmental crisis. The term “Green Concrete” is used for such agricultural wastes that can replace the non-renewable materials in concrete [108, 132, 133]. Portland cement is made by firing calcium carbonate to partial fusion/calcination, requiring 3000–6500 MJ/tonne of clinker energy. Depending on the efficiency of the kiln, CO_2 gas release of the production process can range from 0.67 to 1 ton per ton of cement that contributes to 7% of the total world CO_2 emission as a result of burning fuels, petroleum coke, and fuel oils at about 1500 °C [134-136].

Another motivating factor for researchers is the good potential of palm oil by-products in the construction industry. Oil palm kernel shell (OPKS) is a good example of these by-products used as lightweight aggregate (LWA) in concrete. It reduces the use of natural coarse aggregate, has good density as well as compressive strength, good bonding, and flexural strength, and reduces the cost of concrete manufacturing [137, 138]. Another by-product that has shown good performance and uses less energy than traditional concrete is POFA, a geopolymer that contains a high amount of silica oxide (SiO_2). It can be used as a partial replacement for cement. POFA reduces the effects of sulfate and chloride attack and helps increase drying shrinkage of concrete and decrease heat development [139, 140].

Palm Oil Clinker (POC) is another by-product of palm oil, which is also environmentally friendly and has been used as aggregate replacement. Introducing POC to previous concrete as coarse aggregate reduces the density of the total mixture. It makes it more porous and permeable and lowers its compressive strength [141]. It was also reported that the application of POC as coarse aggregate in concrete reduces modulus of elasticity and splitting tensile strength as well. When applied as a partial sand replacement, it reduces the workability and flexural strength as well as the compressive strength of the total mixtures [142-144]. One way to improve the characteristics of POC is to treat and grind POC into Nano-palm oil **c**linker (NPOC). However, just like POC, the density and compressive strength reduce as the amount of NPOC increases, but the workability of semi-lightweight aggregate concrete improves with the increase in the content of up to 40% [120].

Chemical composition comparison between ordinary portland cement (OPC), POFA, nano palm oil fuel ash (NPOFA), POC, and nano-palm oil clinker powder (NPOCP) is shown in Table 5. From Table 5, it can be shown that a high amount of SiO_2 (High pozzolanic material) for POFA, NPOFA, POC, and NPOCP compared to OPC, which means they can react with other concrete materials.

Even though there are many benefits in using Palm Oil and its by-products in the construction industry, the studies show that the palm oil industry itself plays an important role in releasing a large amount of Nitrogen dioxides (NO_2), Sulphur (SO_2), Carbon monoxide (CO) that are harmful to the environment and natural ecosystems. Another negative impact of this industry is deforestation in Indonesia, Malaysia, and Thailand which are top producers among other countries [21].

Table 5. The chemical composition comparison of ordinary portland cement (OPC) and palm oil waste materials

Chemical Composition, wt %	**OPC** [132]	**OPC** [108]	**OPC** [106]	**OPC** [120]	**POFA** [132]	**POFA** [133]	**POFA** [108]	**NPOFA** [106]	**POC** [141]	**NPOCP** [120]
Silicon Dioxide (SiO_2)	21.45	20.90	26.1	21	48.99	57.8	57.71	67.3	59.90	63.1
Aluminium Oxide (AL_2O_3)	3.62	4.76	8.54	5.9	3.78	2.3	4.56	4.12	3.89	3.2
Iron Oxide (Fe_2O_3)	4.89	3.41	4.09	3.4	3.50	9.6	3.30	8.12	6.93	9
Calcium Oxide (CaO)	60.98	65.41	54.8	64.70	11.69	3.6	6.55	3.97	6.37	4.82
Magnesium Oxide (MgO)	1.22	1.25	0.358	0.027	0.59	1.4	4.23	2.72	3.30	3.5
Sodium Oxide (Na_2O)	0.73	0.24	0.186	0.03	0.25	0.56	0.50	0.115		0.155
Potassium Oxide (K_2O)	0.51	0.35	0.97	0.012	4.01	3.5	8.27	8.45	15.10	12.5
TiO_2	-	-	0.427	0.002	-	0.11	-	0.229	0.29	0.205
P_2O_5	-	-	-	0.012	-	-	-	2.47	3.47	3.09
MnO	-	-	-	0.07	-	-	-	0.07	-	0.118
Mn_2O_3	-	-	-	-	-	-	-	-	-	-
Sulphur Trioxide (SO_3)	2.30	2.71	2.77	2.40	2.25	-	0.25	0.535	0.39	0.152
Loss On Ignition (LOI)	1.37	0.99	-	-	10.51	20.7	10.52	-	1.89	0.00

8. Conclusion and future directions

The use of palm oil and its by-products in bio-asphalt and bio-concrete technologies is an ongoing and relevant research area. This review summarizes the research efforts on the manufacturing of palm oil and its by-product and their applications as bio-oil and bio-char to partially replace petroleum-based asphalt, ordinary Portland cement, or filler in asphalt and concrete mixtures. Bibliometric analysis was conducted to explore the connections between different additive materials and bio-derived materials from palm oil, different test methods, and asphalt binders or concrete mixtures. The VOSviewer mapping ~~could be one of the~~ was utilized to easily ~~ways to~~ highlight the research gaps in the applications of palm oil and its by-product in asphalt and concrete materials. Furthermore, motivations and challenges of using palm oil and its by-product in asphalt and concrete were also highlighted. According to the current review of the literature, the following conclusions can be drawn:

- Many factors affect the bio-asphalt and bio-concrete that are modified with palm oil and its by-product, including the palm oil type, source, chemical and microstructural properties, content, the particle size of biochar that are produced from palm oil derived waste, production process, and so on. Currently, researchers mainly focused on palm oil type, content, and few on microstructural properties. Other factors such as chemical and thermal properties, particle size, and production process needed to be further investigated.

- Palm oil has been shown to maintain similar consistency, viscosity, and stiffness properties of petroleum-based asphalt at oil content lower than 5% which was attributed to the high content of palmitic acid in palm oil that acts as a biopolymer.
- The high content of palm oil reduced the high-temperature rheological performance of asphalt, however, the required mixing and compaction temperatures were decreased and fatigue resistance was enhanced with increasing palm oil to a certain amount.
- Using palm oil as a rejuvenator into RAP materials significantly restored the aging properties of RAP by decreasing the viscosity and stiffness due to chemical interactions and the microstructural properties changes of palm oil in RAP materials. As a result, the percentage of RAP could be maximized with improved fatigue life of RAP.
- The pozzolanic properties of POFA improve compressive strength and resistance to sulphate and chlorine attack, whilst POC has been demonstrated to be more efficient than ordinary sands in lightweight concrete.
- The fineness of POFA plays an important role in concrete. Conversely, the fineness of POFA promotes microfiling and pozzolanic activity, which improves the mechanical and durability of concrete.
- Likewise, the use of all the researched oil palm products such as POFA enhanced the mechanical performance of asphalt mixes in several other aspects, including resilient modulus, fatigue, moisture damage resistance, durability, and rutting due to the pozzolanic cementing properties of POFA. However, incorporating high content of palm oil-derived waste in asphalt mixtures still need further evaluation.
- Overall, the present review of the various types of palm oil and its by-products indicates that the advantages of using such biomaterials in bio-asphalt and bio-concrete include its ability to mitigate the effects of construction material price increases, help in resolving mechanical problems (e.g., through the enhancement of fatigue life of reclaimed asphalt pavement materials and compressive strength of concrete), preserve natural resources by reducing the use of virgin materials like bitumen, and emission reduction.

Compared with the conventional asphalt and concrete mixtures technologies, bio-asphalt and bio-concrete are more sustainable, environmentally friendly, and economic. However, these biotechnologies are still in the initial stages and further research is recommended in the following aspects:

- Generally, huge amounts of palm oil and its by-products are produced worldwide, but there is a very small body of research that has applied CPO as a partial or total replacement for bitumen. Similarly, there are very few studies reported to investigate the possibility of using CPO in different concrete and construction materials technologies.

- Further studies are recommended to investigate the possibility of applications the palm oil in different asphalt mixtures (such as warm-mix asphalt, stone mastic asphalt, cold mix asphalt, and semi-flexible asphalt) and different concrete mixtures (such as lightweight concrete, precast concrete, prestressed concrete, and high-density concrete).
- Future research is also recommended to be conducted on the rheological, chemical, and microstructural properties of bio-based concrete and asphalt binders containing various percentages of palm oil and its by-products at various environmental conditions to extend the knowledge of using such biotechnology for construction materials.
- The physicochemical interaction between palm oil-based materials with different modification technologies such as polymers, nanomaterials, WMA additives, capsulation technology for high and low-temperature applications is also another research gap that should be explored in depth.
- The compressive strength of concrete samples made with POFA, POC, and other palm oil wastes obtained from multiple sources, such as different manufacturers, should be examined to see if the source from which the waste was obtained has any impact on the concrete qualities.
- It is also recommended to incorporate nanoparticles materials such as nanographene and nano-silica into high volume POFA and POC concrete for strength enhancement.
- Further studies/research need to be conducted on the autogenous and drying shrinkage of palm oil wastes modified concrete as well the long-term creep.
- Modeling and simulation the behavior of palm oil and its by-product in asphalt, modified asphalt, composite modified asphalt binders and mixtures, concrete, modified concrete, and composite modified concrete using advanced modeling and simulation techniques such as molecular dynamic, finite element method, and machine learning are also strongly suggested to be further studied.

  Full-scall field performance is also recommended to verify the experimental findings reported by researchers.

Declaration of competing interest

The authors declare no conflict of interest

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References

[1] G. Ali, M.K. Bashir, H. Ali, M.H. Bashir, Utilization of rice husk and poultry wastes for renewable energy potential in Pakistan: An economic perspective, Renewable and Sustainable Energy Reviews 61 (2016) 25-29.

[2] A.M. Al-Sabaeei, M.B. Napiah, M.H. Sutanto, W.S. Alaloul, A. Usman, A systematic review of bio-asphalt for flexible pavement applications: Coherent taxonomy, motivations, challenges and future directions, Journal of Cleaner Production 249 (2020) 119357.

[3] C.-H. Tan, H.M. Ghazali, A. Kuntom, C.-P. Tan, A.A. Ariffin, Extraction and physicochemical properties of low free fatty acid crude palm oil, Food Chemistry 113(2) (2009) 645-650.
[4] U.J. Alengaram, B.A. Al Muhit, M.Z. bin Jumaat, Utilization of oil palm kernel shell as lightweight aggregate in concrete–a review, Construction and Building Materials 38 (2013) 161-172.
[5] S. Sumathi, S. Chai, A. Mohamed, Utilization of oil palm as a source of renewable energy in Malaysia, Renewable and sustainable energy reviews 12(9) (2008) 2404-2421.
[6] P.Y. Gan, Z.D. Li, Econometric study on Malaysia′ s palm oil position in the world market to 2035, Renewable and Sustainable Energy Reviews 39 (2014) 740-747.
[7] S.A. Muhammad, E.-K. Seow, A.M. Omar, A.M. Rodhi, H.M. Hassan, J. Lalung, S.-C. Lee, B. Ibrahim, Variation of δ2H, δ18O & δ13C in crude palm oil from different regions in Malaysia: Potential of stable isotope signatures as a key traceability parameter, Science & Justice 58(1) (2018) 59-66.
[8] U. Nation, Food and Agriculture Organization, 2015. https://www.fao.org/home/en/.
[9] H.M. Hamada, G.A. Jokhio, F.M. Yahaya, A.M. Humada, Y. Gul, The present state of the use of palm oil fuel ash (POFA) in concrete, Construction and Building Materials 175 (2018) 26-40.
[10] M.N. Huda, M.Z.B. Jumat, A.S. Islam, Flexural performance of reinforced oil palm shell & palm oil clinker concrete (PSCC) beam, Construction and Building Materials 127 (2016) 18-25.
[11] A. Johari, B.B. Nyakuma, S.H.M. Nor, R. Mat, H. Hashim, A. Ahmad, Z.Y. Zakaria, T.A.T. Abdullah, The challenges and prospects of palm oil based biodiesel in Malaysia, Energy 81 (2015) 255-261.
[12] M.A. Sukiran, F. Abnisa, W.M.A.W. Daud, N.A. Bakar, S.K. Loh, A review of torrefaction of oil palm solid wastes for biofuel production, Energy Conversion and Management 149 (2017) 101-120.
[13] M.H.M. Yasin, R. Mamat, G. Najafi, O.M. Ali, A.F. Yusop, M.H. Ali, Potentials of palm oil as new feedstock oil for a global alternative fuel: A review, Renewable and Sustainable Energy Reviews 79 (2017) 1034-1049.
[14] M.J. Chin, P.E. Poh, B.T. Tey, E.S. Chan, K.L. Chin, Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective, Renewable and Sustainable Energy Reviews 26 (2013) 717-726.
[15] S. Mekhilef, S. Siga, R. Saidur, A review on palm oil biodiesel as a source of renewable fuel, Renewable and Sustainable Energy Reviews 15(4) (2011) 1937-1949.
[16] A.M. Babalghaith, S. Koting, N.H.R. Sulong, M.R. Karim, B.M. AlMashjary, Performance evaluation of stone mastic asphalt (SMA) mixtures with palm oil clinker (POC) as fine aggregate replacement, Construction and building materials 262 (2020) 120546.
[17] J. Pirker, A. Mosnier, F. Kraxner, P. Havlík, M. Obersteiner, What are the limits to oil palm expansion?, Global Environmental Change 40 (2016) 73-81.
[18] R.J. Hijmans, S.E. Cameron, J.L. Parra, P.G. Jones, A. Jarvis, Very high resolution interpolated climate surfaces for global land areas, International Journal of Climatology: A Journal of the Royal Meteorological Society 25(15) (2005) 1965-1978.
[19] M.A. Friedl, D. Sulla-Menashe, B. Tan, A. Schneider, N. Ramankutty, A. Sibley, X. Huang, MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets, Remote sensing of Environment 114(1) (2010) 168-182.
[20] J.F.D. Tapia, S.S. Doliente, S. Samsatli, How much land is available for sustainable palm oil?, Land Use Policy 102 (2021) 105187.

[21] E. Meijaard, T.M. Brooks, K.M. Carlson, E.M. Slade, J. Garcia-Ulloa, D.L. Gaveau, J.S.H. Lee, T. Santika, D. Juffe-Bignoli, M.J. Struebig, The environmental impacts of palm oil in context, Nature plants 6(12) (2020) 1418-1426.
[22] K. Saswattecha, C. Kroeze, W. Jawjit, L. Hein, Assessing the environmental impact of palm oil produced in Thailand, Journal of cleaner production 100 (2015) 150-169.
[23] K. Saswattecha, C. Kroeze, W. Jawjit, L. Hein, Improving environmental sustainability of Thai palm oil production in 2050, Journal of Cleaner Production 147 (2017) 572-588.
[24] D.o.E.a.S.A. United Nations, Growing of world population at a slower pace 2019. https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html.
[25] K. Tan, K. Lee, A. Mohamed, S. Bhatia, Palm oil: addressing issues and towards sustainable development, Renewable and sustainable energy reviews 13(2) (2009) 420-427.
[26] O. Chavalparit, Clean technology for the crude palm oil industry in Thailand, Wageningen University and Research2006.
[27] C.L. Chew, C.Y. Ng, W.O. Hong, T.Y. Wu, Y.-Y. Lee, L.E. Low, P.S. Kong, E.S. Chan, Improving sustainability of palm oil production by increasing oil extraction rate: A review, Food and Bioprocess Technology 14(4) (2021) 573-586.
[28] K. Chin, P. H'ng, L. Wong, B. Tey, M. Paridah, Production of glucose from oil palm trunk and sawdust of rubberwood and mixed hardwood, Applied energy 88(11) (2011) 4222-4228.
[29] N. Hossain, R. Jalil, Sugar and bioethanol production from oil palm trunk (OPT), Asia Pacific Journal of Energy and Environment 4(1) (2017) 13-16.
[30] P. Singh, O. Sulaiman, R. Hashim, L.C. Peng, R.P. Singh, Using biomass residues from oil palm industry as a raw material for pulp and paper industry: potential benefits and threat to the environment, Environment, development and sustainability 15(2) (2013) 367-383.
[31] H.M. Hamada, G.A. Jokhio, A.A. Al-Attar, F.M. Yahaya, K. Muthusamy, A.M. Humada, Y. Gul, The use of palm oil clinker as a sustainable construction material: A review, Cement and Concrete Composites 106 (2020) 103447.
[32] J.H.V. Purba, Replanting policy of Indonesian palm oil plantation in strengthening the implementation of sustainable development goals, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2019, p. 012012.
[33] L.M. Terry, C. Li, J.J. Chew, A. Aqsha, B.S. How, A.C.M. Loy, B.L.F. Chin, D.S. Khaerudini, N. Hameed, G. Guan, Bio-oil production from pyrolysis of oil palm biomass and the upgrading technologies: A review, Carbon Resources Conversion 4 (2021) 239-250.
[34] K. Muthusamy, Z.N. Azzimah, Exploratory study of palm oil fuel ash as partial cement replacement in oil palm shell lightweight aggregate concrete, Research Journal of Applied Sciences, Engineering and Technology 8(2) (2014) 150-152.
[35] S. Rizal, H. Fizree, M.S. Hossain, D.A. Gopakumar, E.C.W. Ni, H.A. Khalil, The role of silica-containing agro-industrial waste as reinforcement on physicochemical and thermal properties of polymer composites, Heliyon 6(3) (2020) e03550.
[36] M.A.F. Mazlan, Y. Uemura, N.B. Osman, S. Yusup, Fast pyrolysis of hardwood residues using a fixed bed drop-type pyrolyzer, Energy conversion and management 98 (2015) 208-214.
[37] M.J. Iskandar, A. Baharum, F.H. Anuar, R. Othaman, Palm oil industry in South East Asia and the effluent treatment technology—A review, Environmental technology & innovation 9 (2018) 169-185.

[38] I.I.C.E. Outlook, Tracking Progress and Review of Clean Energy Development in Indonesia, Institute for Essential Services Reform: Jakarta, Indonesia (2019).
[39] S. Dey, N. Reang, P. Das, M. Deb, A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel, Journal of Cleaner Production 286 (2021) 124981.
[40] A. Al-Sabaeei, M. Napiah, M. Sutanto, W. Alaloul, A. Ghaleb, Prediction of Rheological Properties of Bio-asphalt Binders Through Response Surface Methodology, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2020, p. 012012.
[41] A.M. Al-Sabaeei, M.B. Napiah, M.H. Sutanto, S. Rahmad, N.I.M. Yusoff, W.S. Alaloul, Determination of rheological properties of bio-asphalt binders through experimental and multilayer feed-forward neural network methods, Ain Shams Engineering Journal (2021).
[42] A. Behnood, M.M. Gharehveran, Morphology, rheology, and physical properties of polymer-modified asphalt binders, European Polymer Journal 112 (2019) 766-791.
[43] C. Chen, J.H. Podolsky, R.C. Williams, E.W. Cochran, Laboratory investigation of using acrylated epoxidized soybean oil (AESO) for asphalt modification, Construction and Building Materials 187 (2018) 267-279.
[44] W. Rafiq, M. Napiah, N.Z. Habib, M.H. Sutanto, W.S. Alaloul, M.I. Khan, M.A. Musarat, A.M. Memon, Modeling and design optimization of reclaimed asphalt pavement containing crude palm oil using response surface methodology, Construction and Building Materials 291 (2021) 123288.
[45] A.F.J. Uchoa, W. da Silva Rocha, J.P.M. Feitosa, R.L. Nogueira, D.H.A. de Brito, J.B. Soares, S. de Aguiar Soares, Bio-based palm oil as an additive for asphalt binder: Chemical characterization and rheological properties, Construction and Building Materials 285 (2021) 122883.
[46] M.Y. Alamawi, F.H. Khairuddin, N.I.M. Yusoff, K. Badri, H. Ceylan, Investigation on physical, thermal and chemical properties of palm kernel oil polyol bio-based binder as a replacement for bituminous binder, Construction and Building Materials 204 (2019) 122-131.
[47] F.H. Khairuddin, M.Y. Alamawi, N.I.M. Yusoff, K.H. Badri, H. Ceylan, S.N.M. Tawil, Physicochemical and thermal analyses of polyurethane modified bitumen incorporated with Cecabase and Rediset: Optimization using response surface methodology, Fuel 254 (2019) 115662.
[48] A.M. Al-Sabaeei, M.B. Napiah, M.H. Sutanto, W.S. Alaloul, N.I.M. Yusoff, F.H. Khairuddin, A.M. Memon, Evaluation of the high-temperature rheological performance of tire pyrolysis oil-modified bio-asphalt, International Journal of Pavement Engineering (2021) 1-16.
[49] A.M. Al-Sabaeei, M. Napiah, M. Sutanto, W. Alaloul, N.I.M. Yusoff, M.I. Khan, S.M. Saeed, Physicochemical, rheological and microstructural properties of Nano-Silica modified Bio-Asphalt, Construction and Building Materials 297 (2021) 123772.
[50] M.N. Borhan, A. Ismail, R.A. Rahmat, Evaluation of palm oil fuel ash (POFA) on asphalt mixtures, Australian Journal of Basic and Applied Sciences 4(10) (2010) 5456-5463.
[51] E. Khankhaje, M. Rafieizonooz, M.R. Salim, R. Khan, J. Mirza, H.C. Siong, Sustainable clean pervious concrete pavement production incorporating palm oil fuel ash as cement replacement, Journal of cleaner production 172 (2018) 1476-1485.
[52] N.S.A. Yaro, M.B. Napiah, M.H. Sutanto, A. Usman, S.M. Saeed, Performance Evaluation of Waste Palm Oil Fiber Reinforced Stone Matrix Asphalt Mixtures Using Traditional and Sequential Mixing Processes, Case Studies in Construction Materials (2021) e00783.

[53] N. Yaro, M. Napiah, M. Sutanto, A. Usman, S. Saeed, J. Kaura, Influence of modification mixing parameters on conventional properties of palm oil clinker fine (POCF)-modified bitumen, Materials Today: Proceedings (2021).
[54] R.R. Daud, J. Tanijaya, Study of HRS-WC Mixture Performance Using the Waste of Crude Palm Oil Ash as Filler, The 3rd International Conference on Civil and Environmental Engineering (ICCEE), 2020, pp. 1755-1315.
[55] A. Shuaibu, H. Otuoze, I. Iliyasu, U. Maska, Effect Of Oil Palm Mesocarp Fibre Ash (Opmfa) On The Strength Properties Of Hot Mix Asphalt, ATBU Journal of Science, Technology and Education 8(2) (2020) 336-350.
[56] G. Rusbintardjo, M.R. Hainin, N.I.M. Yusoff, Fundamental and rheological properties of oil palm fruit ash modified bitumen, Construction and Building Materials 49 (2013) 702-711.
[57] R.R. Zulkefli, H. Yaacob, R.P. Jaya, M. Warid, N. Hassan, M. Hainin, M. Idham, Effect of different sizes of palm oil fuel ash (POFA) towards physical properties of modified bitumen, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2018, p. 012108.
[58] A.M.M. Sukaimi, R.N.A.R. Zulkefli, H. Yaacob, R.P. Jaya, N.A. Hassan, M.N.M. Warid, M.K.I.M. Satar, Effect of grinding period on physical properties of modified bitumen using palm oil fuel ash (POFA), Journal of Physics: Conference Series, IOP Publishing, 2018, p. 012004.
[59] K.R. Usman, M.R. Hainin, M.K.I.M. Satar, M.N.M. Warid, S.N.N. Kamarudin, S. Abdulrahman, Palm oil fuel ash application in cold mix dense-graded bituminous mixture, Construction and Building Materials 287 (2021) 123033.
[60] M. Abu Yousef, S. Amin, Experimental feasibility study of using date palm oil as a bitumen Bio-Modifier in HMA pavement, (2020).
[61] N.S.A. Yaro, M.B. Napiah, M.H. Sutanto, A. Usman, S.M. Saeed, Modeling and optimization of mixing parameters using response surface methodology and characterization of palm oil clinker fine modified bitumen, Construction and Building Materials 298 (2021) 123849.
[62] A.M. Babalghaith, S. Koting, N.H.R. Sulong, M.R. Karim, S.A. Mohammed, M.R. Ibrahim, Effect of palm oil clinker (POC) aggregate on the mechanical properties of stone mastic asphalt (SMA) mixtures, Sustainability 12(7) (2020) 2716.
[63] A.M. Maleka, I.A. Alkali, R.P. Jaya, The indirect tensile strength of Palm Oil Fuel Ash (POFA) modified asphaltic concrete, Applied Mechanics and Materials, Trans Tech Publ, 2014, pp. 1270-1275.
[64] A.M. Maleka, A.W. Hamad, R.P. Jaya, Effect of Palm Oil Fuel Ash (POFA) on the durability of asphaltic concrete, Applied Mechanics and Materials, Trans Tech Publ, 2015, pp. 1560-1565.
[65] M.R. Hainin, R.P. Jaya, N. Ali Akbar, D.S. Jayanti, N.I.M. Yusoff, Influence of palm oil fuel ash as a modifier on bitumen to improve aging resistance, Journal of Engineering Research 2(1) (2014) 34-46.
[66] N. Yaro, M. Napiah, M. Sutanto, A. Usman, A. Rafindadi, S. Saeed, S. Abdulrahman, Evaluation of the impact of short-term aging on volumetric and Marshall properties of palm oil clinker fine modified asphalt concrete (POCF-MAC), Journal of Physics: Conference Series, IOP Publishing, 2021, p. 012054.
[67] K. Usman, M. Hainin, M. Satar, M. Warid, M. Bilema, A. Usman, A. Zulfiqar, Durability of POFA-modified dense-graded cold mix asphalt, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022, p. 012006.
[68] S.A.P. Rosyidi, B. Idiajir, N.M. Akhir, S. Rahmad, N.P. Lestari, V. Widoanindyawati, A.M. Al-Sabaeei, A. Milad, N.S. Mashaan, N.I. Md Yusoff, Physical, Chemical and

Thermal Properties of Palm Oil Boiler Ash/Rediset-Modified Asphalt Binder, Sustainability 14(5) (2022) 3016.
[69] A. Kargari, M. Arabani, S.M. Mirabdolazimi, Effect of palm oil capsules on the self-healing properties of aged and unaged asphalt mixtures gained by resting period and microwave heating, Construction and Building Materials 316 (2022) 125901.
[70] R.R. Zulkefli, H. Yaacob, R.P. Jaya, M.N.M. Warid, N. Hassan, M.R. Hainin, M. Idham, Effect of different sizes of palm oil fuel ash (POFA) towards physical properties of modified bitumen, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2018, p. 012108.
[71] K.R. Usman, M.R. Hainin, M.K.I.M. Satar, M.N.M. Warid, I.A. Adamu, A.A.M. Radwan, Performance-Based Design for Binary-Blended Filler Application in Dense-Graded Cold Mix Asphalt, Road and Airfield Pavement Technology, Springer2022, pp. 529-545.
[72] T. Syammaun, H. Rani, Resilient modulus of porous asphalt using oil palm fiber, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018, p. 012023.
[73] M.M.A. Aziz, A.W. Hamad, A.M. Maleka, F.M. Jakarni, Effect of viscoelastic behavior of cellulose oil palm fiber (COPF) modified 60-70 asphalt binder for deterioration for roads and highways, Jurnal Teknologi 75(11) (2015).
[74] F. Moghadas Nejad, A. Azarhoosh, G.H. Hamedi, H. Roshani, Rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements, Road Materials and Pavement Design 15(1) (2014) 207-219.
[75] A. Al-Sabaeei, M. Napiah, M. Sutanto, W. Alaloul, Effects of Waste Denim Fibre (WDF) on the physical and rheological properties of bitumen, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019, p. 012047.
[76] W.N.A.W. Azahar, R.P. Jaya, M.R. Hainin, M. Bujang, N. Ngadi, Chemical modification of waste cooking oil to improve the physical and rheological properties of asphalt binder, Construction and Building Materials 126 (2016) 218-226.
[77] R. Mamat, M.R. Hainin, N.A. Hassan, N.A.A. Rahman, M.N.M. Warid, M. Khairul, AReview OF PERFORMANCE ASPHALT MIXTURES USING BIO-BINDER AS ALTERNATIVE BINDER, JURNAL TEKNOLOGI 77(23) (2015) 17-20.
[78] S. Pouget, F. Loup, Thermo-mechanical behaviour of mixtures containing bio-binders, Road Materials and Pavement Design 14(sup1) (2013) 212-226.
[79] D. Sun, G. Sun, Y. Du, X. Zhu, T. Lu, Q. Pang, S. Shi, Z. Dai, Evaluation of optimized bio-asphalt containing high content waste cooking oil residues, Fuel 202 (2017) 529-540.
[80] M. Gong, J. Yang, J. Zhang, H. Zhu, T. Tong, Physical–chemical properties of aged asphalt rejuvenated by bio-oil derived from biodiesel residue, Construction and Building Materials 105 (2016) 35-45.
[81] B. Hill, D. Oldham, B. Behnia, E.H. Fini, W.G. Buttlar, H. Reis, Evaluation of low temperature viscoelastic properties and fracture behavior of bio-asphalt mixtures, International Journal of Pavement Engineering 19(4) (2018) 362-369.
[82] Z. Lei, T. Yi-qiu, H. Bahia, Relationship between glass transition temperature and low temperature properties of oil modified binders, Construction and Building Materials 104 (2016) 92-98.
[83] C.-P. Tan, I.A. Nehdi, The physicochemical properties of palm oil and its components, Palm Oil, Elsevier2012, pp. 377-391.
[84] Z. Haron, S. Ghalip, K. Yahya, N. Darus, H. Halim, R.N. Mohamed, Palm Oil Clinker AS Noise Control Materials, (2021).
[85] M. Safiuddin, M.Z. Jumaat, Fresh properties of self-consolidating concrete incorporating palm oil fuel ash as a supplementary cementing material, Chiang Mai Journal of Science 38(3) (2011) 389-404.

[86] N. Ranjbar, A. Behnia, B. Alsubari, P.M. Birgani, M.Z. Jumaat, Durability and mechanical properties of self-compacting concrete incorporating palm oil fuel ash, Journal of Cleaner Production 112 (2016) 723-730.
[87] B. Alsubari, P. Shafigh, M.Z. Jumaat, U.J. Alengaram, The effect of palm oil fuel ash as a cementreplacement material on self-compacting concrete, Applied Mechanics and Materials, Trans Tech Publ, 2014, pp. 529-534.
[88] B. Alsubari, P. Shafigh, Z. Ibrahim, M.F. Alnahhal, M.Z. Jumaat, Properties of eco-friendly self-compacting concrete containing modified treated palm oil fuel ash, Construction and Building Materials 158 (2018) 742-754.
[89] M. Salam, M. Safiuddin, M. Jumaat, Durability indicators for sustainable self-consolidating high-strength concrete incorporating palm oil fuel ash, Sustainability 10(7) (2018) 2345.
[90] R.H. Kupaei, U.J. Alengaram, M.Z.B. Jumaat, H. Nikraz, Mix design for fly ash based oil palm shell geopolymer lightweight concrete, Constr. Build. Mater. 43 (2013) 490-496.
[91] M.A.M. Ariffin, M.A.R. Bhutta, M.W. Hussin, M. Mohd Tahir, N. Aziah, Sulfuric acid resistance of blended ash geopolymer concrete, Constr. Build. Mater. 43 (2013) 80-86.
[92] M.Y.J. Liu, U.J. Alengaram, M. Santhanam, M.Z. Jumaat, K.H. Mo, Microstructural investigations of palm oil fuel ash and fly ash based binders in lightweight aggregate foamed geopolymer concrete, Constr. Build. Mater. 120 (2016) 112-122.
[93] E. Khankhaje, M.W. Hussin, J. Mirza, M. Rafieizonooz, M.R. Salim, H.C. Siong, M.N.M. Warid, On blended cement and geopolymer concretes containing palm oil fuel ash, Materials & Design 89 (2016) 385-398.
[94] A.A. Kadir, N.A.M. Zahari, N.A. Mardi, Utilization of palm oil waste into fired clay brick, Advances in Environmental Biology 7(12) (2013) 3826-3835.
[95] A. Elhusna, Wahyuni, The compressive strength and the absorption of the clay brick with the rice husk ash and the palm oil fuel ash, Proceeding of the International Conference on Engineering and Science for Research and Development (ICESReD), 2016, pp. 19-23.
[96] A.R. Djamaluddin, M.A. Caronge, M. Tjaronge, R. Irmawaty, Fired clay bricks incorporating palm oil fuel ash as a sustainable building material: an industrial-scale experiment, International Journal of Sustainable Engineering (2020) 1-13.
[97] M.W. Tjaronge, M.A. Caronge, Physico-mechanical and thermal performances of eco-friendly fired clay bricks incorporating palm oil fuel ash, Materialia 17 (2021) 101130.
[98] B.S. Mohammed, W. Foo, M. Abdullahi, Flexural strength of palm oil clinker concrete beams, Materials & Design 53 (2014) 325-331.
[99] B.S. Mohammed, W. Foo, K. Hossain, M. Abdullahi, Shear strength of palm oil clinker concrete beams, Materials & Design 46 (2013) 270-276.
[100] J. Kanadasan, A.F.A. Fauzi, H.A. Razak, P. Selliah, V. Subramaniam, S. Yusoff, Feasibility studies of palm oil mill waste aggregates for the construction industry, Materials 8(9) (2015) 6508-6530.
[101] F. Abutaha, H. Abdul Razak, H.A. Ibrahim, Effect of coating palm oil clinker aggregate on the engineering properties of normal grade concrete, Coatings 7(10) (2017) 175.
[102] K. Wi, H.-S. Lee, S. Lim, H. Song, M.W. Hussin, M.A. Ismail, Use of an agricultural by-product, nano sized Palm Oil Fuel Ash as a supplementary cementitious material, Construction and Building Materials 183 (2018) 139-149.
[103] A.S.M.A. Awal, M.W. Hussin, The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction, Cement and Concrete Composites 19(4) (1997) 367-372.
[104] M.A. Megat Johari, A.M. Zeyad, N. Muhamad Bunnori, K.S. Ariffin, Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash, Construction and Building Materials 30 (2012) 281-288.

[105] B. Alsubari, P. Shafigh, M.Z. Jumaat, Development of Self-Consolidating High Strength Concrete Incorporating Treated Palm Oil Fuel Ash, Materials 8(5) (2015).
[106] H.M. Hamada, F.M. Yahaya, K. Muthusamy, G.A. Jokhio, A.M. Humada, Fresh and hardened properties of palm oil clinker lightweight aggregate concrete incorporating Nano-palm oil fuel ash, Construction and Building Materials 214 (2019) 344-354.
[107] M. Amran, Y.H. Lee, R. Fediuk, G. Murali, M.A. Mosaberpanah, T. Ozbakkaloglu, Y. Yong Lee, N. Vatin, S. Klyuev, M. Karelia, Palm Oil Fuel Ash-Based Eco-Friendly Concrete Composite: A Critical Review of the Long-Term Properties, Materials 14(22) (2021).
[108] W. Tangchirapat, T. Saeting, C. Jaturapitakkul, K. Kiattikomol, A. Siripanichgorn, Use of waste ash from palm oil industry in concrete, Waste Management 27(1) (2007) 81-88.
[109] A.S.M. Abdul Awal, M. Warid Hussin, Effect of Palm Oil Fuel Ash in Controlling Heat of Hydration of Concrete, Procedia Engineering 14 (2011) 2650-2657.
[110] E. Aprianti, P. Shafigh, S. Bahri, J.N. Farahani, Supplementary cementitious materials origin from agricultural wastes – A review, Construction and Building Materials 74 (2015) 176-187.
[111] F. Moghaddam, V. Sirivivatnanon, K. Vessalas, The effect of fly ash fineness on heat of hydration, microstructure, flow and compressive strength of blended cement pastes, Case Studies in Construction Materials 10 (2019) e00218.
[112] K.A. Mujedu, M.A. Ab-Kadir, N.N. Sarbini, M. Ismail, Microstructure and compressive strength of self-compacting concrete incorporating palm oil fuel ash exposed to elevated temperatures, Construction and Building Materials 274 (2021) 122025.
[113] B.S. Thomas, S. Kumar, H.S. Arel, Sustainable concrete containing palm oil fuel ash as a supplementary cementitious material – A review, Renewable and Sustainable Energy Reviews 80 (2017) 550-561.
[114] B. Alsubari, P. Shafigh, M.Z. Jumaat, Utilization of high-volume treated palm oil fuel ash to produce sustainable self-compacting concrete, Journal of Cleaner Production 137 (2016) 982-996.
[115] J.H. Tay, Ash from Oil‐Palm Waste as a Concrete Material, Journal of Materials in Civil Engineering 2(2) (1990) 94-105.
[116] N. Ranjbar, A. Behnia, B. Alsubari, P. Moradi Birgani, M.Z. Jumaat, Durability and mechanical properties of self-compacting concrete incorporating palm oil fuel ash, Journal of Cleaner Production 112 (2016) 723-730.
[117] J.P. Hwang, H.B. Shim, S. Lim, K.Y. Ann, Enhancing the durability properties of concrete containing recycled aggregate by the use of pozzolanic materials, KSCE Journal of Civil Engineering 17(1) (2013) 155-163.
[118] T.Z. Ting, M.Z. Ting, M.E. Rahman, V. Pakrashi, Palm Oil Fuel Ash: Innovative Potential Applications as Sustainable Materials in Concrete, (2020).
[119] M. Amin, A.M. Zeyad, B.A. Tayeh, I.S. Agwa, Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates, Construction and Building Materials 302 (2021) 124196.
[120] H. Hamada, A. Alattar, F. Yahaya, K. Muthusamy, B.A. Tayeh, Mechanical properties of semi-lightweight concrete containing nano-palm oil clinker powder, Physics and Chemistry of the Earth, Parts A/B/C 121 (2021) 102977.
[121] K. Muthusamy, N.F.A. Jamaludin, M.N. Kamaruzzaman, M.Z. Ahmad, N.A. Zamri, A.M.A. Budiea, Compressive strength of palm oil clinker lightweight aggregate concrete containing coal bottom ash as sand replacement, Materials Today: Proceedings 46 (2021) 1724-1728.
[122] H. Mohammadhosseini, R. Alyousef, N.H.A.S. Lim, M.M. Tahir, H. Alabduljabbar, A.M. Mohamed, Creep and drying shrinkage performance of concrete composite comprising

waste polypropylene carpet fibres and palm oil fuel ash, Journal of Building Engineering 30 (2020) 101250.
[123] S. Tasnim, Y. Du, M.E. Rahman, R.B. Ahmadi, S.I. Doh, Effect of using palm oil fuel ash on the durability of cement paste in ammonium nitrate solution, Construction and Building Materials 257 (2020) 119597.
[124] A.M. Alnahhal, U.J. Alengaram, S. Yusoff, R. Singh, M.K. Radwan, W. Deboucha, Synthesis of sustainable lightweight foamed concrete using palm oil fuel ash as a cement replacement material, Journal of Building Engineering 35 (2021) 102047.
[125] A. Alaskar, H. Alabduljabbar, A.M. Mohamed, F. Alrshoudi, R. Alyousef, Abrasion and skid resistance of concrete containing waste polypropylene fibers and palm oil fuel ash as pavement material, Construction and Building Materials 282 (2021) 122681.
[126] C. Rajesh, G.N. Sameer, M.S.M. Reddy, D.C.K. Jagarapu, P.K. Jogi, Consumption of palm oil fuel ash in producing lightweight concrete, Materials Today: Proceedings 33 (2020) 1073-1078.
[127] P. Chindaprasirt, S. Homwuttiwong, C. Jaturapitakkul, Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash, Construction and Building Materials 21(7) (2007) 1492-1499.
[128] A.A. Jhatial, W.I. Goh, T.A. Rind, A. Kumar, Thermal performance simulation of eco-friendly lightweight foamed concrete incorporating palm oil fuel ash and eggshell powder using ABAQUS, Silicon (2021) 1-21.
[129] W. Chalee, T. Cheewaket, C. Jaturapitakkul, Enhanced durability of concrete with palm oil fuel ash in a marine environment, Journal of Materials Research and Technology 13 (2021) 128-137.
[130] H. Alabduljabbar, H. Mohammadhosseini, M.M. Tahir, R. Alyousef, Green and sustainable concrete production using carpet fibers waste and palm oil fuel ash, Materials Today: Proceedings 39 (2021) 929-934.
[131] V.S. Nadh, G.S. Vignan, K. Hemalatha, A. Rajani, Mechanical and durability properties of treated oil palm shell lightweight concrete, Materials Today: Proceedings (2021).
[132] A. Budiea, M. Hussin, K. Muthusamy, M. Ismail, Performance of high strength POFA concrete in acidic environment, Concr. Res. Lett 1(1) (2010) 14-18.
[133] K. Abid, R. Gholami, G. Mutadir, A pozzolanic based methodology to reinforce Portland cement used for CO2 storage sites, Journal of Natural Gas Science and Engineering 73 (2020) 103062.
[134] Z. He, X. Zhu, J. Wang, M. Mu, Y. Wang, Comparison of CO2 emissions from OPC and recycled cement production, Construction and Building Materials 211 (2019) 965-973.
[135] M. Ali, R. Saidur, M. Hossain, A review on emission analysis in cement industries, Renewable and Sustainable Energy Reviews 15(5) (2011) 2252-2261.
[136] L. Vizcaíno-Andrés, S. Sánchez-Berriel, S. Damas-Carrera, A. Pérez-Hernández, K. Scrivener, J. Martirena-Hernández, Industrial trial to produce a low clinker, low carbon cement, Materiales de Construcción 65(317) (2015) e045-e045.
[137] D.C. Teo, M.A. Mannan, J.V. Kurian, Flexural behaviour of reinforced lightweight concrete beams made with oil palm shell (OPS), Journal of advanced concrete technology 4(3) (2006) 459-468.
[138] B.S. Thomas, S. Kumar, H.S. Arel, Sustainable concrete containing palm oil fuel ash as a supplementary cementitious material–A review, Renewable and Sustainable Energy Reviews 80 (2017) 550-561.
[139] W. Tangchirapat, S. Khamklai, C. Jaturapitakkul, Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates, Materials & Design 41 (2012) 150-157.

[140] N.M. Altwair, M.M. Johari, S.F.S. Hashim, Influence of treated palm oil fuel ash on compressive properties and chloride resistance of engineered cementitious composites, Materials and structures 47(4) (2014) 667-682.
[141] H.A. Ibrahim, H.A. Razak, Effect of palm oil clinker incorporation on properties of pervious concrete, Construction and Building Materials 115 (2016) 70-77.
[142] F. Abutaha, H.A. Razak, J. Kanadasan, Effect of palm oil clinker (POC) aggregates on fresh and hardened properties of concrete, Construction and Building Materials 112 (2016) 416-423.
[143] F. Abutaha, H.A. Razak, H.A. Ibrahim, H.H. Ghayeb, Adopting particle-packing method to develop high strength palm oil clinker concrete, Resources, conservation and Recycling 131 (2018) 247-258.
[144] M. Sulaiman, M. Ali, M. Al-Amri, K. Muthusamy, A.A. Budiea, N. Nordin, Y. Duraisamy, R. Othman, Properties of Concrete Containing Crushed Palm Oil Clinker as Partial Fine Aggregate Replacement, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, p. 012020.