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Mustafa Kamal Tun Abdul Aziz
Suzana Yusup
Editors

Sustainable Technologies for the Oil Palm Industry

Latest Advances and Case Studies

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Dominic C. Y. Foo would like to dedicate this book to his wife Cecilia and their daughters Irene, Jessica and Helena. They are his driving force in developing various cutting-end technologies for a sustainable future.

Mustafa Kamal Tun Abdul Aziz would like to dedicate this book to his late father Tun (Dr.) Abdul Aziz Abdul Majid and mother Toh Puan Raja Teh Zaitun Kamarulzaman, wife Noor Azian, sons Abdul Muhaimin and Abdul Aziz, his late student Dr. Mohd Halim Syah Ismail as well as the well-respected the late Royal Professor Ungku Aziz bin Ungku Abdul Hamid.

Suzana Yusup would like to dedicate this book to her parents Yusup Abd Rasip and Salmah Baba, her husband Mohamad Zaki Yusof, her sons Mohamad Akmal, Mohamad Hazim , Mohamad Harith and daughter Nur Atikah. Their understanding, support and encouragement are the key to her journey towards advancing sustainable greener processes and technologies.

Foreword

I am delighted to congratulate the editors and authors of this excellent book *Sustainable Technologies for the Oil Palm Industry—Latest Advances and Case Studies*. It encompassed the latest work of both industrial players and academia for the sustainable oil palm industry, with emphasis on various novel disruptive technologies for the oil palm business and radical innovative processes. Certainly, the book is in line with the commitment of Council of Palm Oil Producing Countries (CPOPC) in furthering the United Nations Sustainable Development Goals (UNSDG).

I am aware that the same group of editors and authors produced the earlier book *Green Technologies for the Oil Palm Industry* in 2019. It serves as a good guide for many practitioners in seeking for latest innovations in green technologies for the oil palm industries. So I hope this second book with a focus on sustainable technologies is equally beneficial to the oil palm industrial players. It is a sign of the strength and continuity of sustainable oil palm research and development, as well as Malaysia commitments to scientific and evidence-based research.

Let me conclude by wishing the editors and authors a big success for this book. Judging from its outstanding content, I am sure it will contribute to the primary roles of palm oil and palm biomass to the economic benefits of the producers, while putting environmental sustainability as a primary focus for the benefits of global consumers. This will ensure a long and stable low-carbon economy and global food security future for all.

Jakarta, Indonesia

Tan Sri Datuk Dr. Yusof Basiron
Executive Director of Council of Palm
Oil Producing Countries (CPOPC)

Preface

Palm oil is the most widely used edible oil in the world. Being the second-largest world producer and exporter of palm oil, Malaysia exported 16.2 million metric tonnes (MT) of palm oil and palm-based products in the year 2020, valued at approximately 73.3 billion Malaysian ringgit (approximately 17.5 billion USD). In the same year, the oil palm industry contributed about 2.7% or 36.87 billion Malaysian ringgit (approximately 8.78 billion USD) to the gross domestic product (GDP) of Malaysia (www.statista.com).

In recent years, major efforts have been put to enhance sustainability aspects of palm oil products. The Roundtable on Sustainable Palm Oil was established since the year 2004 to develop and implement environmental-friendly standards in palm oil production. As an effort to promote sustainability, various new technologies were reported in our last book published in 2019—*Green Technologies for the Oil Palm Industry* with Springer Nature. Since its publication, the book has received an overwhelming response in the oil palm industrial sector as it serves as a guide for promoting the use of green technologies. As a follow-up, this book is meant to promote some recent developed sustainable/green technologies for the oil palm industry. It comprises 14 chapters outlining the state-of-the-art advances in various aspects of palm biomass and palm oil processing from renowned scholars and industrial practitioners. These chapters may be read independently of each other without a particular sequence. Synopses of the chapters are given as follows.

Synopses of Chapters in Part One—Disruptive Technologies for Palm Biomass

This part consists of eight chapters on various disruptive technologies developed for palm biomass-based processes in recent years, ranging from experimental research, computational tools and industrial practices. The first chapter by Law and Foo entitled "Maximizing Valorisation Opportunities from Palm Biomass" provides an overview of various innovations involving the conversion of biomasses into value-added products. In Chapter Two entitled "Aviation Biofuels: Conversion Routes and Challenges", Chong and co-workers discuss the opportunities and challenges of sustainable production of jet biofuel. In Chapter Three entitled "Oil Palm-Based Nanocellulose: From Extraction to Applications", a comprehensive review was reported for palm-based nanocellulose from its initial isolation, characterisations to the final applications. Chapter Four by Perera and co-workers, entitled "Effect of Nanolignin and Nanocrystalline Cellulose on Thermal, Mechanical, and Water Barrier Properties of Starch Composites", discusses a ternary biopolymer composite that was obtained by reinforcing thermoplastic starch with nanocrystalline cellulose and nanolignin from oil palm empty fruit bunch.

The few following chapters reported some computational tools for various biomass processes. Chapter Five entitled "Process Simulation and Scheduling of Bio-succinic Acid Production from Palm Biomass" by Foo and co-worker reported process modelling and scheduling of bio-succinic acid production from palm biomass. In Chapter Six entitled "Stochastic Modeling for Palm Biomass Supply Chain", How and co-worker presented an overview of key supply chain uncertainties that should be incorporated into the biomass supply chain model. In Foo's Chapter Seven entitled "Process Integration Tools for Optimal Allocation of Palm Biomass", two process integration tools, i.e. graphical pinch diagram and mathematical programming model, were presented to determine the optimal allocation of palm biomass for bioenergy production. In the final chapter of this part entitled "Innovations to a Palm Biomass–Fueled Power Plant", industrial practitioners Lakshmanan and co-workers described some changes made for the water tube boiler to improve its fuel handling and combustion efficiency, which allowed handling of fibre with higher moisture content.

Synopses of Chapters in Part Two—Innovations in Palm Oil Processing

This part consists of six chapters that have their focus on various innovations in palm oil processing. Chapter Nine by Lim and co-worker entitled "Mathematical Modelling and Optimisation for Fresh Fruit Bunch Harvesting and Evacuation" proposed a potential solution to the labour-intensive fresh fruit bunch harvesting and evacuation process using mathematical optimisation modelling approach. In Chapter Ten entitled "Zero-Waste Technologies for the Sustainable Development of Oil Palm Mills", Teow and co-workers described an integrated technology for zero-waste oil palm processing in addressing the challenges of highly polluting effluent, greenhouse gases emission and solid waste generation. Two following chapters focus on the treatment of palm oil mill effluent. In Chapter Eleven entitled "Advancement in Various Stages of Palm Oil Mill Effluent (POME) Treatment Process", three established methods to modernise POME treatment are described by Khadaroo and co-worker. Chapter Twelve entitled "Performance and Stability of Pre-commercialized Integrated Anaerobic–Aerobic Bioreactor (IAAB) for the Treatment of Palm Oil Mill Effluent (POME)" next reported the performance of a pre-commercialised integrated anaerobic–aerobic bioreactor under variable organic loadings and environmental conditions with respect to effluent quality and methane yield. In Chapter Thirteen entitled "3-MCPDE in Palm Oil Processing: Formation Factors, Transference to Food and Mitigation Approaches" by Chew and co-workers, the formation factors and mitigation strategies of process contaminant, i.e. 3-monochloro-1, 2-propanediol esters (3-MCPDE), are discussed. In the final chapter entitled "Sustainable Practices of IOI Palm Oil and Palm Kernel Processing Complex in Sabah", industrial practitioners reported various sustainable practices carried out in a palm oil and kernel processing complex, resulted in 85% recovery of treated effluent and 40% reduction of power consumption, apart from improved product quality and lower treatment chemical usage.

Together, these 14 chapters present some latest advancements of sustainable technologies in the oil palm industry. It is hoped that the idea and innovations in these chapters will motivate readers in nurturing a sustainable palm oil industry.

Selangor, Malaysia

Dominic C. Y. Foo
Mustafa Kamal Tun Abdul Aziz
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Contents

Disruptive Technologies for Palm Biomass

Maximizing Valorisation Opportunities from Palm Biomass

Albert Yuen Hong Law and Dominic C. Y. Foo

Abstract Malaysia is the second largest world palm oil producer. The oil palm industry has been the main contributor of biomasses to Malaysia. These biomasses can be turned into various value-added bio-based products that are in high demand, such as bioenergy, bio-agriculture, eco-products, and bio-chemicals. In this chapter, the availability of various palm biomasses in Malaysia, and its current industry practices were reviewed. The innovations involving the conversion of biomasses into value-added products were outlined. Challenges to unlock the potential of the underutilized biomasses are further discussed.

Keywords Value-added products · Empty fruit bunch · Palm kernel shell · Oil palm trunk · Oil palm frond · Mesocarp fiber

1 Introduction

Crude palm oil (CPO) is the main product of the oil palm industry. Fresh fruit bunch harvested from the oil palm plantation is sent to a typical palm oil mill (POM), where CPO is produced through a series of pressing actions to the fruit. The leftover wastes from the CPO production process include the empty fruit bunches (EFBs), mesocarp fiber (MF), palm kernel shell (PKS), and palm oil mill effluent (POME). While these are typically viewed as wastes, it is a fact that the multiple trails of biomasses left behind the CPO production should be treated as “opportunities”. In the past decades, various technologies and innovations have transformed the biomasses into feedstock and/or bioenergy. It has been proven that the oil palm biomass can be converted into solid biofuel in pellets, briquettes, or shell forms, which can replace coal for energy

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generation. Besides, through bio-chemical extraction, it can be converted to bio-ethanol, medical grade alcohol, bio-diesel, or even sugar, and many other possibilities that are waiting to be harnessed, i.e., bio-fertilizer, biogas power generation, eco-fiber matt, raw material for mattresses and bio-composite, etc. In other words, treating biomass as waste is an outdated view.

The National Biomass Strategy 2020 (Agensi Inovasi Malaysia (AIM), 2013) blueprint projected that Malaysia to produce up to 80 million tons of biomass annually, with a big majority from the oil palm sector. The biomass industry itself has an enormous potential to drive a sustainable and circular economy in the country.

The demand for bioenergy is rising, especially in East Asian countries such as Japan, China, South Korea, and those in the Europe. Some of these countries are already importing biofuel pellets (Northport (Malaysia) Bhd., 2021; Department of Statistics Malaysia, 2021a), and palm kernel shells (Department of Statistics Malaysia, 2021b) from Malaysia, Indonesia, and Vietnam. Although some might argue that this highly policy-dependence industry has no longevity in its current form, it has been reported that more biomasses are now replacing fossil fuels in the energy industry in the above-mentioned countries.

At present, the traceability of the palm biomass is being scrutinized. The main principle is to ensure that these biomasses come from the waste streams. According to MIGHT 2019 (Malaysia Industry-Government Group for High Technology (MIGHT), 2019) MITI 2018/2019 review (Ministry of International Trade and Industry, 2019), as well as the Roundtable on Sustainable Palm Oil (2021) certification, sustainability and chain of custody are the requirements of the importing countries. Nevertheless, the fact remains that substantial portion of these biomasses is still underutilized. Hence, the enormous potential should be explored, and its unexpected challenges should be addressed.

The palm biomass may be categorized into those that originated from the plantation activities, and those from the milling operations. These are discussed in the following sections. This chapter provides an overview of the following:

- Types of biomasses produced from both plantations and mills,
- Characteristics of each type of raw biomass, and
- Market potential and industrial utilization.

The information herein was based on personal interviews and experiences accumulated over the years with various industry players. The chapter summarizes those understandings, views, and recommendations of those experiences and interviews.

2 Oil Palm Plantations in Malaysia

Malaysia is blessed with a humid tropical climate that comes with ample of sunshine and evenly distributed annual rainfall. This promotes the growth of oil palm trees and its CPO production under this optimal condition, which has led to tremendous contribution to gross domestic product of Malaysia in the past four decades.

To date, Indonesia and Malaysia have become the epicenter of the booming palm oil production, which resulted in the extensive expansion of palm oil plantation area. Since 1960s, Malaysia government has identified oil palm as a key agricultural crop apart from rubber. The Malaysian Palm Oil Board (MPOB) reported that there are about 5.9 million ha (MPOB 2021) of oil palm planted areas nationwide at the end of 2020, which is equivalent to about 25% of Malaysia's total land area. This includes 2.8 million ha of plantation in Peninsular Malaysia, 1.5 million ha in Sabah, and 1.6 million ha in Sarawak (MPOB 2021). Figure 1 shows the locations of oil palm plantations in Malaysia.

The palm plantations are owned by large conglomerates (e.g., IOI, Sime Darby, KLK), governmental agencies (i.e.: FELDA and FELCRA) (Teoh, 2002) and independent smallholders (see Fig. 2). Back in the 1990s, under the encouragement from the government to promote growth, urbanization, and infrastructure developments in rural areas, a surge of oil palm plantation and industry could be seen through various government programs such as 2nd–11th Malaysia Plan, National Key Economic Areas (NKEA) policies (World Bank Group, 2019), etc. The industry is export-oriented and hence serves as one of the major contributors to Malaysia's national revenue.

Oil palm yield is about ten times higher than that of soybean (Singh et al., 2021), and usually needs 26–33 months for the planted sapling to bear mature fresh fruit bunch (FFB) ready for harvest. On average, a hectare of mature palm trees can produce 1.3–1.6 tons of FFB monthly (dan Komoditi, 2019). Each of these FFB weighs 10–25 kg (Ismail & Mamat, 2002) and it bears fruits all year long. The production of FFB for year 2019 is reported to be 99.3 million tons (see Fig. 3).

The oil palm tree can grow up to 6 m and have a life span of 30 years, MPOB recommends 25 years replanting cycle for the oil palm plantations (Eco Synergy Solutions Sdn, 2017). Normally, one hectare of palm plantation is generally planted with to 132–150 oil palm trees (Malaysian Palm Oil Board (MPOB), 2011), depending on terrain and other factors.

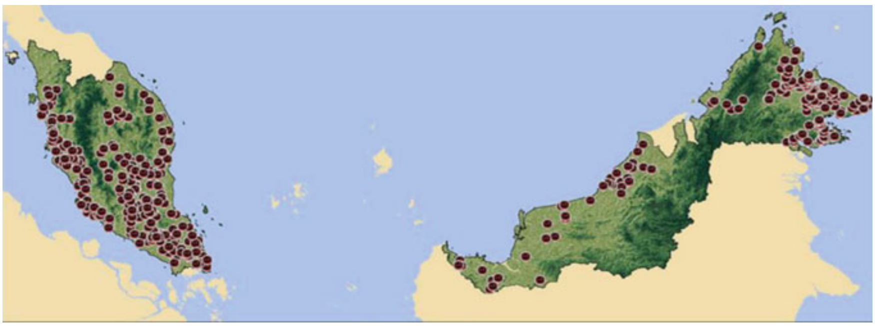


Fig. 1 Locations of oil palm plantation in Malaysia (EU-Malaysia Chamber of Commerce and Industry (EUMCCI), 2017)

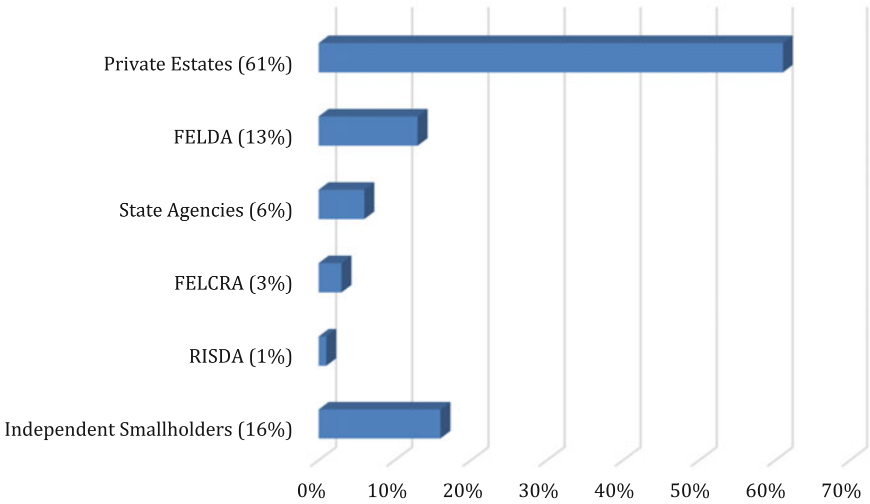


Fig. 2 Stakeholders distribution of oil palm plantation (Hasan et al., 2019)

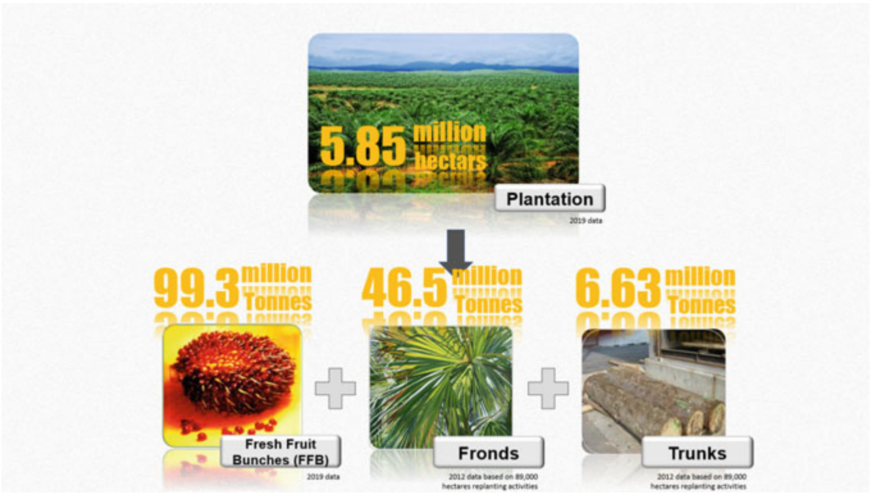


Fig. 3 Overview of biomasses from Malaysia oil palm Plantation of 2019 (World Bank Group, 2019)

3 Biomass from Plantations

3.1 Oil Palm Trunks (OPT)

Oil palm trunks (OPT, Fig. 4) become available at the end of a plantation's life cycle, i.e., every 25–30 years. As a rule of thumb, it is estimated that 74.48 (Zulkifli et al., 2010) tons of OPT biomass could be generated of each hectare of palm oil plantation during a replanting operation. For year 2018, a total of 6.63 million tons of OPT was generated (see Fig. 3).

Note that the replanting schedule and quantity of available OPT are not directly correlated with the age of oil palm trees that is to be replanted. Instead, it depends on the CPO market price and owner discretion. MPOB recommended replantation to take place when trees grow above the age of 26 (Nambiappan et al., 2018). However, the palm replanting effort has not been encouraging despise encouragement of the government agencies. It is estimated that one-sixth of matured plantation in Malaysia has surpassed its optimum fruit yield period. Hence, this led to reduced CPO and hence biomass production.

There are assorted reasons for the hesitation of replanting among the conglomerate's management. These include factors such as the nature of palm oil production cycle, volatility of CPO market price, invariably association between rising costs of production and falling profit (due to deteriorating fruit yield), and sudden changes of international purchasing policy. The smallholders however face different obstacles on the other hand. These include difficulties to do proper replanting (for those with crops are in the forest areas), excessive cost for difficult terrain replanting, incompletion

Fig. 4 Freshly harvested OPT stacked and waiting to be transported out of the replanting field during replanting operation (photo taken in Kluang, Johor)

Fig. 5 Tree felling, chipping of OPT into chunks and pieces for natural decomposing process for nutrient recovery to the plantation

of smallholders' legal documents, lack of other sources of income during the grace period, and limited operational budget for replanting, etc. Furthermore, smallholders have difficulty accessing loan from banks due to the lack of third-party guarantors for small replanting projects. These unstable reasons halted OPT in becoming a stable supply of biomass feedstock for industrial-scale downstream projects. Hence, oil palm trunks are left to decay in the plantation area (Bukhari et al., 2019). This is indeed a major loss of business opportunity.

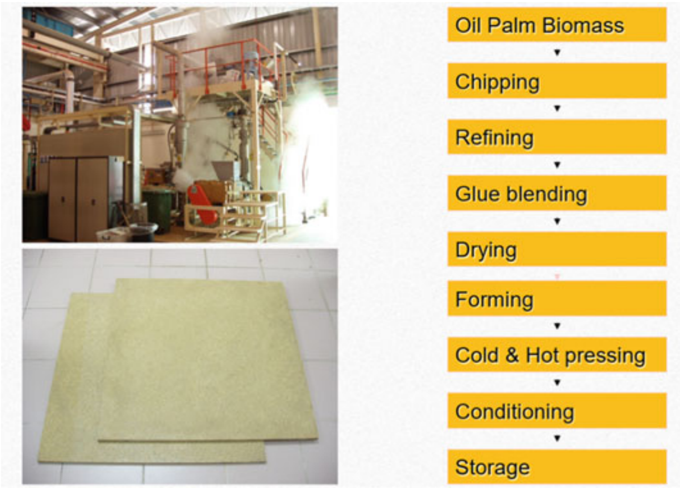
3.1.1 Opportunities of OPT Biomass as Natural Fertilizer

Current practice of the industrial players is to retain the OPT in the plantation as fertilizer. Trunks are either felled or chipped to allow for quicker return of nutrients to the soil. Alternatively, they are killed with poison and left standing to decompose naturally in the field (Fig. 5). A small percentage of trunks are currently used in the wood industry, e.g., plywood, medium-density fiberboard (MDF) (Rosli et al., 2016), and energy generation (Ibrahim et al., 2014a)

3.1.2 Opportunities of OPT as Raw Material for Plywood

The wood from the oil palm tree cannot be used as timber directly, as it is softwood with high moisture content. Extensive research was conducted to convert OPT into plywood and medium-density fiberboard. It is a mature technology that has been commercialized and deployed (Ibrahim et al., 2014b) (see Fig. 6). However, in author's opinion, there are challenges that need to be addressed and overcome before these technologies are ready for commercialization:

- Inconsistency of raw material supply because its availability is dependent on decision of plantation owners.
- For plantations in the rural area, harvesting, collection, and transportation costs for the site may be higher than the cost–benefit curve.



(a)

(b)

Fig. 6 Steps to produce **a** MDF; **b** MDF production (photos are courtesy of Dongwha MDF Fiberboard Commercialization trial plant)

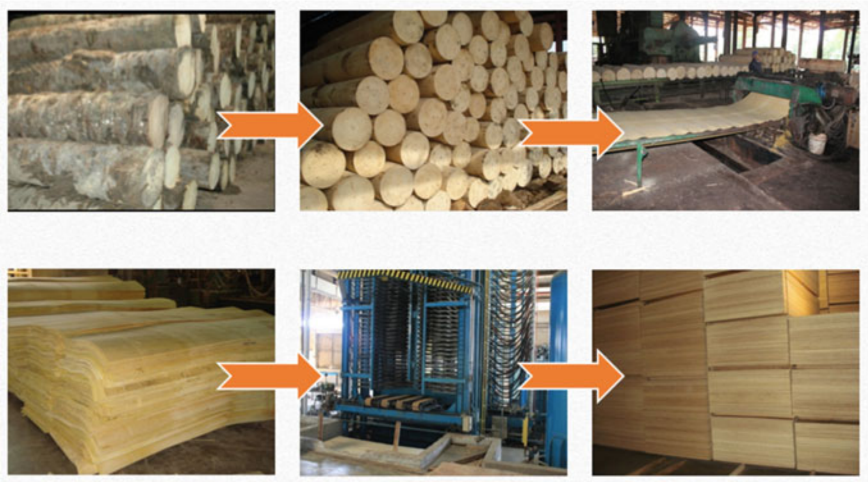


Fig. 7 Process of plywood production (*Courtesy picture from MPOB Palm Plywood processing research)

- Due to its soft nature, the final product does not have the same quality as other fiberboards in terms of durability to heat, pressure, thus have lower acceptability in the existing market.

As a rule of thumb, an OPT of 18 ft long can be used to produce about 40 pieces of wood veneers (with size of 2 ft × 8 ft) of 4 mm of thickness. Alternatively, the 18 ft long OPT can also be made into seven pieces of veneers, each with thickness of 12 mm.

Even though OPT is a good candidate for the deprived plywood market. However, due to its weaker durability, most harvested OPT is not being used. This left behind some waste in the plywood-making process. Besides, OPT is not woody material anatomically. Therefore, the produced plywood (Fig. 7) can only meet the minimum strength requirement according to the Japanese Standard Method (JAS 233:2003), which resulted in less attractive profit margin. That might be the reason why OPT plywood does not have large-scale production, even though it is technically viable and achievable. It is also worth mentioning that to achieve desired productivity in operations and product quality, some modifications are necessary for the processing techniques and equipment, such as blade and the intake size of the chipping machine.

3.1.3 Opportunities of OPT as Raw Material for Solid Biofuel

In recent years, it has been a global trend in seeking alternative energy for the replacement of fossil fuels. As such, palm pellet (Fig. 8) has been identified as favorite for global energy storage. It is a natural entry point a biomass owner can capitalize almost

Fig. 8 Palm pellet made from OPT

immediately, as the technology is reasonably mature, while the cost of developing infrastructure is relatively low. Hence, the project has short payback period.

Apart from its obvious function as an energy deliverance for the energy sector, pellet is also a very cost-effective way to mobilize the huge, bulky, highly moist biomasses for long distances. It is arguably that large-scale palletization of OPT is an efficient way of energy reservoirs for regional energy security.

Palm pellets in Malaysia have been shipped to Japan and Korea as a renewable energy source in recent years. There is also market demand for pellets from European energy utility companies where European renewable energy targets are to be met. Similarly, Japan is sourcing biomass for co-firing to ensure sufficient energy supply given its reduction in nuclear energy capacity. Unfortunately, the current Malaysian pellet is unable to meet these needs in terms of production volume, and standardization of its quality requirement, as well as its policy compliances.

Even though the palm pellet industry has a bright future, it does face some challenges. Malaysia pellet industry is currently shaping its self-regulating standardization to meet the quality requirement of the importing countries. Besides, there is no clear longevity policy and demand on Malaysian biomass pellet from importing countries like Japan and Korea. In other words, the absence of a ready market is still the major obstacle for the biomass pellet business currently.

3.1.4 Opportunities of OPT as Raw Material for Bioproduct and Biofuel

Due to its relatively high sugar content in the trunk sap, OPT may be considered for bioethanol production, which in turn can be used as biofuel. Production of bioethanol via fermentation of sugars and to be blended with gasoline has always been seen as a wise strategy. Apart from being able to reduce dependency on fossil fuels, this sustainable alternative fuel helps to reduce carbon footprints. There is on-going effort is trying to unlock the potential of OPT sap (Jalil & Hossain, 2015) for bioethanol production. This pilot plant scale effort has successfully optimized the usage of sugar content within OPT sap as carbon source. One could now conclude that OPT sap provides major advantages for bioconversion due to the following reasons:

- the process is inexpensive,
- no additional chemical or enzymatic treatment is needed,
- excellent properties in terms of sugars, nitrogen, amino acids, vitamins, and minerals, hence good yield of desired products,
- low quantity of by-products from the process which makes the fermentation process economically viable.

There are numerous flickering sparks and initial successful pilot biofuel projects in several areas with high density of palm plantation. A full commercial-scale bioconversion complex is also expected in the coming future.

3.2 Oil Palm Fronds (OPF)

Oil palm fronds (OPFs) are obtained during replanting activities, pruning of oil palm trees, and harvesting of FFBs, with the latter accounting for the greatest share of volume. It has been estimated that about 14.47 tons/ha of OPF can be gathered from pruning activities, while 15 tons/ha of OPF could be gathered when a plantation is being replanted. It is logical to assume that the OPF availability is depending on FFB harvesting activities (Onoja et al., 2018). It was reported that a total of 46.5 million tons of OPF was generated for year 2019 (see Fig. 3).

The OPF is approximately 2–3 m long and weighs about 10 kg (wet weight; see Fig. 9). It consists of two main parts, i.e., the petiole (stem) and many long leaflets on either side of the stem. The top two-thirds of the frond contains most of the nutrients, while the basal (lower) third is rich in cellulosic materials and sugars, which are needed in the production of biofuels and bio-based chemicals.

Frond pruning of oil palm trees significantly affects fruit bunch production. Trees without frond pruning produce lesser and lighter bunches comparing to those with excessive pruning below 32 fronds (Agensi Inovasi Malaysia (AIM), 2013). This leads to the abundant availability of OPF all year round following the regular industry frond pruning practices.

3.2.1 Opportunities of OPF as Natural Fertilizer Through Natural Decomposition

Most OPFs are left in the oil palm plantation in the current practice. Even if there is any collection activity of OPF from the field, only the basal portion, i.e., one-third of the fronds are being collected for downstream uses. The remaining parts of the

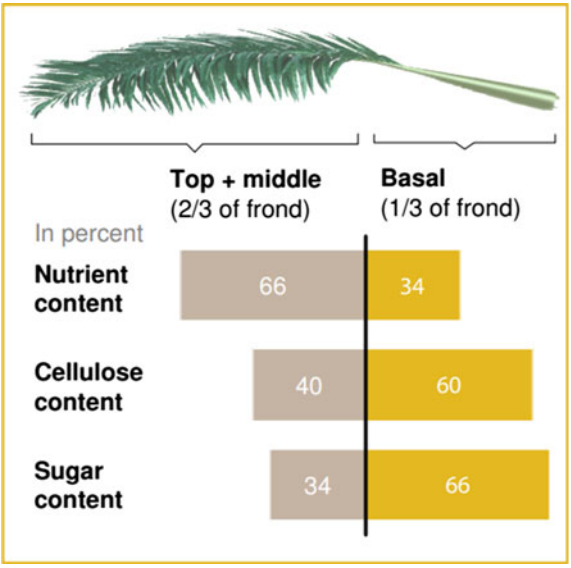


Fig. 9 Structure and contents of OPF (Agensi Inovasi Malaysia (AIM), 2013)

frond (top and middle portion) which contain most of the nutrients (mulch or whole) are left as topsoil replacement and natural fertilizer. The basal portion may be made available for fibers production, feeds for livestock, biofuels, or bio-based chemicals.

During the replanting activity, the teared down midrib is arranged in the soil to become line marker for the field work and as organic fertilizer. They also help to maintain soil moisture and avoid erosion to certain extent.

Due to its bulky nature, the OPF collection methods range from simple manual collection with a wheelbarrow, animal cart, or motor-cart, to advanced mechanization, which varies with collection cost. Terrain problem (e.g., elevation, spacing of trees, rivers, and holes), labor constraints, and economies of scale are among reasons why OPF have yet to reach its maturity as raw material for downstream innovation projects at industrial scale.

3.2.2 Opportunities of OPF as Animal Feeds for Livestock

OPFF contains high fibrous materials which can be further processed as ruminant animals' feed (Fig. 10). OPF has been widely utilized as feedstock in the form of freshly chopped, silage, pellets, or cubes form. Mixture made from freshly chopped OPF and palm kernel cake has been extensively used by local farmers for feeding beef and dairy cattle in Malaysia. Many studies have been reported to raise feed conversion efficiency (FCE) and average daily gain (ADG), with an acceptable ratio of 20% OPF: 80% PKC-based mixture diet. Note however that this does not show promising economics (Zahari et al., 2002). A mixture diet containing OPF and PKC with ratio of 40:60 is most economical as indicated by cost per weight gain value

Fig. 10 OPF as livestock feeds

[26]. Hence, the optimum OPF inclusion level for beef and dairy animals feed is at about 30% in their diet from the economical perspective, i.e., feed cost per weight gain value.

3.2.3 Other Commercial Potential of OPF

There are other potential applications for OPF. It has been reported that OPF could also be used as a starting material to produce bio-composites for high-performance applications (Suhaily et al., 2012; Rasat et al., 2014). The substitution of petroleum-based materials with this natural fiber would reduce the dependency on imported oil thus contributing greatly to overall cost-effectiveness.

There is also potential to make use of OPF juice in producing biofuels (Lim and Ibrahim, 2012; Kumneadklang et al., 2015) (bio-ethanol primarily) and bio-based chemicals such as bio-plastics (Zahari et al., 2015), nutraceuticals (Ofori-Boateng, 2013), etc. Note however that the available technology is yet to reach its mature stage, and hence the utilization of OPF on large industrial scale is yet to be seen.

4 Palm Biomass from Processing Activities in POM

In 2020, there were 457 POMs in operation in Malaysia (Malaysia Palm Oil Board MPOB, 2020) (see Fig. 11). The main product from the POMs is CPO which is mainly used as cooking oil and many other palm products. A total of 19,140,613 tons of CPO was produced in year 2020 (Malaysia Palm Oil Board MPOB, 2020), which made Malaysia the second world CPO producer.

In the POMs, CPO is produced from FFB after undergoing a series of purification processes. The milling operations also generate a significant amount of biomass. Figure 12 shows the biomass from the milling process include FFB, mesocarp fiber, palm kernel shell (PKS), as well as the liquid effluent known as POME.

Although large amount of palm biomass is available in Malaysia, there are no official statistics announced by the authority. This is because biomass has no official custodian ministry or agency to date. Hence, the palm industry normally adopts "guesstimation" approach in obtaining biomass data. Figure 13 shows amount of solid biomass produced for every ton of FFB processed. As shown, approximately 22% of the processed FFB becomes EFB, 12% turns into mesocarp fiber, while 5.5% is as palm kernel shell. Besides, about 60.75 litter of POME is produced. Note however that these figures are based on general rules of estimation in the oil palm industry. As each POM has different operating conditions (e.g., energy consumption practices, automation-oriented or labor dependency, management principles, etc.), their biomass yield may differ from these figures.

Fig. 11 Number of palm oil mills in Malaysia by states, 2020 (Malaysia Palm Oil Board MPOB, 2020)

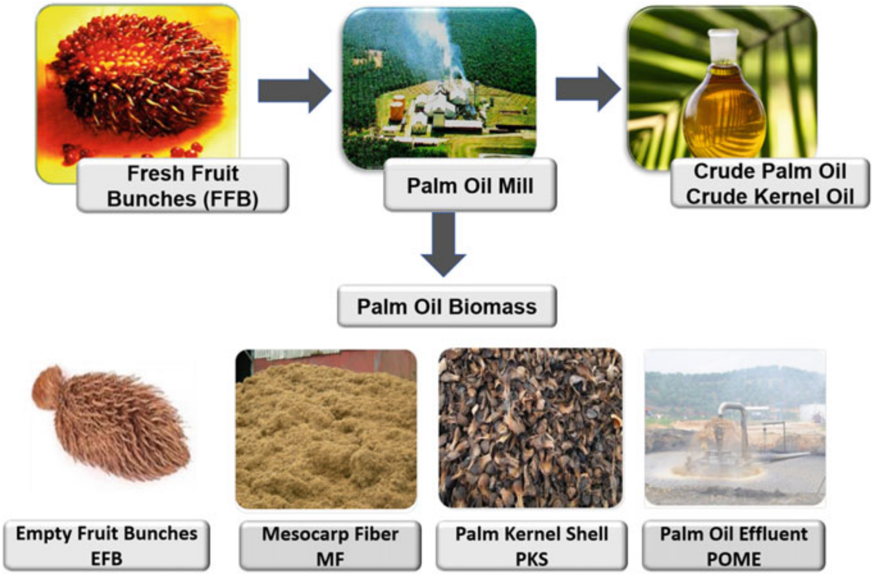


Fig. 12 Different types of biomasses produced from a POM

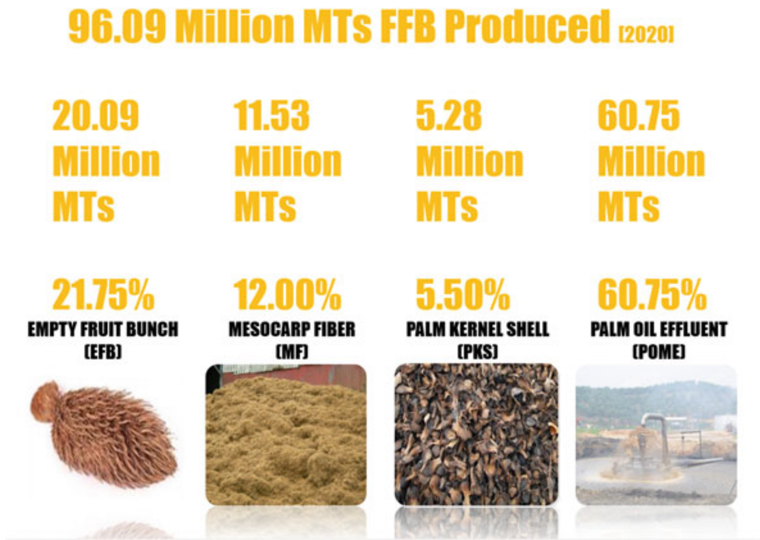


Fig. 13 Different types of biomasses generated from POM, calculative estimation to industrial best knowledge

4.1 Empty Fruit Bunch (EFB)

EFB is the remains after removal of oil from the FFB. The upstream process of separating the palm fruits from the bunch involves cooking of bunch with steam under high pressure, which is followed by threshing operation. These operations lead to separation of fruits from the bunches, with disposal of the "empty" fruit bunch (see Fig. 14).

It is estimated that for each ton of FFB processed, 21% of EFB is generated. For year 2020 where 96 million tons of FFB that have being processed, it was estimated that a slightly over 20 million tons of EFB was produced from the entire Malaysia palm industry (Fig. 13).

In current industrial practices, some EFBs are utilized for steam and power generation in the mill, or other niche downstream applications (see discussion in the later section), note however that a large portion (estimated three quarters) of EFB is used for nutrient replacement and mulching purposes in the plantations, or worse landfilling within the POM premise. These are considered as loss of opportunity, as EFB can be converted to other value-added products.

However, there are technical hurdles that need to be overcome before the EFB can be better utilized. Firstly, EFB is bulky. Its length may be as 50 cm and weighs up to 20 kg per bunch. This increases the cost of transportation significantly and preventing them for downstream utilization. Furthermore, these highly moist EFBs must be processed within 3 days after its disposal from the mill. Failing to do so leads to fermentation process where the EFBs will start rotting. Note that the above-mentioned issues do not occur in other biomass types, such as wood waste. Fortunately, technological breakthrough has enabled EFB to be utilized in various forms of consumer products. These are discussed in the following sub-sections.

4.1.1 EFB as Natural Fertilizer

For many decades, EFBs were burned in an open air, and its ashes are used as soil-treatment agents or fertilizer. However, the rising awareness of environmental

Fig. 14 Fresh fruit bunch (FFB) is processed in the palm oil mill, which resulted with palm fruit and empty fruit bunch (EFB)

sustainability and air pollution has led to the enforcement of legislation that prohibited this traditional practice.

However, utilization of EFB to field mulching and composting is a long-standing practice of the industry and is still widely being carried out (Fig. 15). Other benefits of this practice include better weed control, prevention of soil erosion, and moisture retention in the soil. Note however that there are opposing views on this practice, arguing that it is merely a cost-effective way of disposing of the EFBs, as compared to the alternative such as landfilling within the mill area, which is land consuming, hazardous, and costly. Note however that in the recent years, the main problem encountered with mulching practices is the rising cost of labor and transportation. These factors have led to the increasing cost of the mulching process.

On the other hand, EFB compost treatment is a more cost-effective and environmental-friendly option. It turns EFB into a usable compost. This process reduces the bulkiness of EFB so that it is more cost-effective for transportation and distribution work at the plantation fields. It also retains the benefit of protecting the soil and crops by reducing the risk of weed seeds, parasites, and pathogens spreading, while enjoying lower transportation costs.

EFB may also be composted along with POME. Apart from cost reduction (due to co-treatment of both by-products), EFB compost treatment also provides another product for the POM with saleable value (Fig. 16). Generally, there are two methods practiced by the industry, i.e., indoor and outdoor composting processes. Each method uses EFB, other organic materials and mostly couples those with POME as part of the ingredient. In both processes, this compost will be mixed and turned and introduced

Fig. 15 EFB mulching in the plantation

Fig. 16 Indoor composting process and outdoor composting process, turning EFB and POME into sellable compost

with its own "cocktails recipe" of enzyme to increase its yield. However, as the name suggested, the outdoor composting process is fully exposed to nature, hence the composting process is harder to manage and control. Hence, in general, the indoor composting process is much well-managed and its outcome is also more controllable.

4.1.2 Fiberized EFB and Its Opportunities

Technological breakthroughs for EFB happened in the 1990s, where successful mechanical shredding and fiberizing of EFB were reported. The fiberization of EFB enables various value-added products to be introduced in the market. Among them, the production of EFB pellets as solid biofuels has attracted many small and medium enterprises (SMEs) to venture into the business. These fuel pellets and briquettes made from palm EFB are meant for the export market (Fig. 17a). These solid fuels are used for both small-scale home heating and large-scale power generation. Besides the EFBs are made into dried long fiber, to be used as raw material for consumable mattresses (Fig. 17b). These are primarily aimed for China market as a replacement of coil fibers for mattresses manufacturing. The fibrous nature of EFB with a lower price (as compared to coil fibers) allows the mattresses industry to reduce its production cost. Besides, fiber mats for soil erosion prevention or for agriculture seed bedding purposes can also be made from EFB (Fig. 17c).

Yet another area that attracted good attention is eco-products. There are several companies that venture into the production of pulp and paper, as well as stationaries products from EFB fibers in Malaysia. Another promising sub-sector that shows

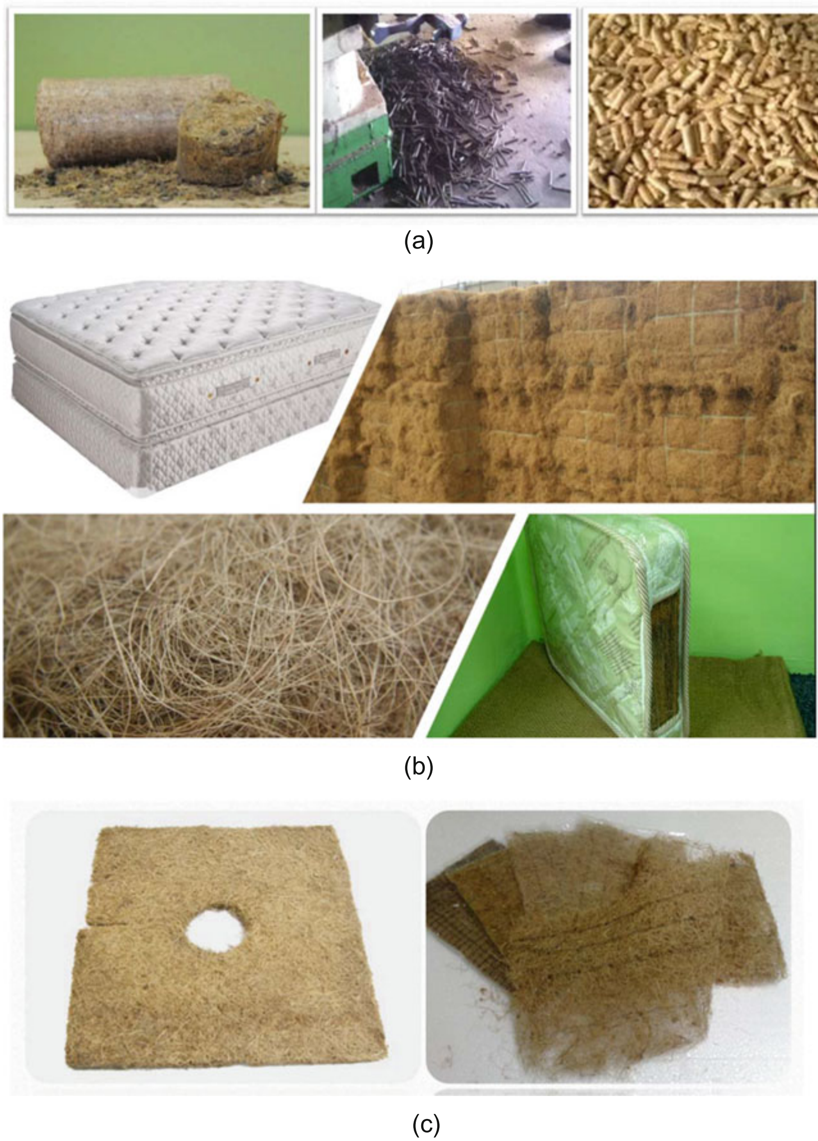


Fig. 17 **a** Different types of solid biofuel produced from EFB; **b** dried long fiber made from EFB which is then weaved into mattresses; **c** soil erosion control fiber mat (courtesy of Global Green Synergy Sdn. Bhd. and Fibromat (M) Sdn. Bhd.)