Green Energy and Technology

Dominic C. Y. Foo
Mustafa Kamal Tun Abdul Aziz *Editors*

Green Technologies for the Oil Palm Industry

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Dominic C. Y. Foo would like to dedicate this book to his wife Cecilia, his kids Irene, Jessica and the new born baby Helena.

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, as well as to Noor Azian, Abdul Muhaimin and Abdul Aziz.

Foreword

The Malaysian oil palm industry has faced various challenges since its first commercial planting in Malaysia in 1917. Over the last 100 years, the industry has faced health, nutrition and environmental issues. We have always been at the forefront in responding to these numerous challenges. Malasia is often seen as the leading innovator in managing the requirements of sustainability, conservation and economic development in a balanced manner, in line with the 3Ps (People, Planet, Profit) and the UN's Sustainable Development Goals (SDGs).

However, more and rigorous sustainability demands are being made on agro-based industries globally. This is particularly true for the energy sector, which has been targeted for the accelerated effects of climate change coupled with the release of more greenhouse gas (GHG) emissions, despite adaptations of renewable energy mandate. This has led to the emergence of green technologies which aim provide more environment-friendly and sustainable forms of renewable energy.

The Malaysian oil palm sector is fortunate to be gifted with a multitude of green technologies. For example, methane gas captured at palm oil mills that can reduce up to 40% of palm oil's GHG emissions and utilising oil palm biomass such as empty fruit bunches, fronds, shells, and trunks to produce renewable energy, second-generation biofuels and bio-based chemicals, are providing key drivers for oil palm cultivators.

This book focuses on the innovative utilisation of green technologies in palm oil milling processes, and how these innovations enhance the values found in the palm oil supply chain. While such innovations are technically viable, the real challenge would be their adoption in the commercial environment.

Finally, we would like to congratulate the editors for initiating this project and making this publication a reality. We hope that the book would be a useful reference to the oil palm industry that is looking to explore and adopt new green technology innovations in their pursuit of higher sustainability commitments.

Petaling Jaya, Malaysia

Datuk Dr. Kalyana Sundram
Chief Executive Officer
Malaysian Palm Oil Council (MPOC)

Preface

The palm oil industry is an important commodity sector in Malaysia. Oil palm tree originated in West Africa and was planted in Peninsular Malaysia as earlier as 1917. Significant growth in the plantation area was observed in the 70s, following the collapse of the global price of rubber (which was the main agricultural output of Malaysia back then).

The Malaysia Palm Oil Board (MPOB) reported that in the year 2017, Malaysia had 5.81 million hectares of oil palm planted area and produced approximately 20 million MT of crude palm oil (CPO). Total exports of oil palm products (palm oil, palm kernel oil, palm kernel cake) were reported at 23.97 million MT, contributing to the total export revenue increasing to RM 77.85 billion (approximately USD 19.5 billion). The three main export markets for Malaysian palm oil are India (2.03 million MT, 12.2% of total palm oil exports), the European Union (1.99 million MT, 12.0%) and China (1.92 million MT, 11.6%). On the other hand, the EU was the major export market for palm kernel oil (0.25 million MT, 25.9%), followed by China (0.17 million MT, 17.6%) and Turkey (0.08 million MT, 8.3%). For palm kernel cake (PKC), the major export markets in 2017 were New Zealand (0.65 million MT, 29.4% of total PKC export) and the EU (0.48 million MT, 21.9%).

Even though the trading records have seen a healthy growth in the long run, the palm oil industry does suffer some recurring issues, such as low oil extraction rate (MPOB reported the 2017 national oil extraction rate as 19.7%), labour-intensive and some controversial issues on sustainability, e.g. deforestation. It is also worth noting that the availability of cheap foreign labour has suppressed the initiative for innovation in the palm oil industry.

This book is meant to address some of the above issues. It comprises eight chapters outlining the state-of-the-art advances in palm oil milling processes from renowned experts and researchers. These chapters may be read independently of each other without a particular sequence. Synopses of all chapters are given as follows.

Synopses of Chapters in Part I—New Technologies for Palm Oil Mills

This part consists of four chapters on new technologies developed for the palm oil milling processes. Chapter "Flowsheet Synthesis and Optimisation of Palm Oil Milling Processes with Maximum Oil Recovery" by Foong and co-workers describes an optimisation model that can be used for synthesising a palm oil milling process flow sheet that maximises oil recovery. In Chapter "Alternative Solvent Design for Oil Extraction from Palm Pressed Fibre via Computer Aided Molecular Design", computer-aided molecular design (CAMD) tool was used to design alternative solvent for oil extraction from palm-pressed fibre. Chapter "Green Extraction Process for Oil Recovery Using Bio-Ethanol" by Abdul Aziz and co-workers discusses process development for green extraction processes for waste oil recovery. Chapter "Palm Oil Mill Effluent (POME) Treatment—Current Technologies, Biogas Capture and Challenges" by Chan and Chong outlines the state-of-the-art techniques for POME treatment, as well as the latest technologies developed for biogas capture, which is commonly carried out in Malaysian palm oil mill.

Synopses of Chapters in Part II—Palm Biomass and Biomass Supply Chain

This part consists of four chapters that focus on palm biomass and its supply chain problems. Chapter "Numerical Methods to Estimate Biomass Calorific Values via Biomass Characteristics Index" by Tang et al. describes the development of a new index that may be used to estimate calorific values for various biomass. Foo's Chapter "A Simple Mathematical Model for Palm Biomass Supply Chain" describes a linear programming model that can be used to determine optimum allocation of biomass. The next chapter, How's "An Overview of Palm Biomass Supply Chain Modelling", describes the state-of-the-art techniques for detailed modelling and optimisation of a palm biomass supply chain. Finally, Chapter "Cooperative Game Theory Analysis for Implementing Green Technologies in Palm Oil Milling Processes", by Andiappan et al., introduces the eco-industrial park concept for the oil palm industrial players.

Together, these eight chapters present some newly developed green technologies in the palm oil industry. It is our hope that the readers will be inspired by the idea and innovation discussed in these chapters, which might then help to add value to the palm oil industry and its value chain.

Semenyih, Malaysia

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First and foremost, we wish to thank the authors who contributed their invaluable expertise in the form of chapters covering various green technologies in palm oil processing. The value of this book is based primarily on their inputs. We are also grateful to the staff of Springer Nature, who provided invaluable assistance throughout the long process of publication.

Both editors would like to acknowledge the Ministry of Higher Education, Malaysia, for providing Long Term Research Grant Scheme (LRGS; UPM/700-1/3/LRGS—Enhancing Productivity and Sustainability of Palm Oil Milling Industry) that funded some of the research activities between the years 2013–2018.

Finally, we would like to thank our family members for their support throughout our professional careers. In particular, Dominic Foo would like to thank his wife Cecilia Cheah for the tremendous support, especially in taking care of their kids—Irene, Jessica and Helena. Mustafa Kamal would like to acknowledge his research officers Noor Baini Binti Nabila Mohamad and Mohd Rizuan Bin Mansor for their dedicated research work and Universiti Teknologi Sdn Bhd (UTSB) for managing the LRGS fund.

Dominic C. Y. Foo
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Contents

Part I
New Technologies for Palm Oil Mills

Flowsheet Synthesis and Optimisation of Palm Oil Milling Processes with Maximum Oil Recovery

Steve Z. Y. Foong, Viknesh Andiappan, Dominic C. Y. Foo and Denny K. S. Ng

Abstract Crude palm oil (CPO) is produced in palm oil mills (POMs) using fresh fruit bunches (FFBs), harvested from oil palm plantations. FFB passes through multiple unit operations in the milling process, each consists of different technologies. Palm oil millers have tried to improve the milling technologies collectively and individually to enhance the extraction efficiency, meeting the process and product requirements. However, oil lost in the milling process remains the major issue in POM and leads to heavy loss of profit. In order to address such issue, oil recovery technologies were introduced and implemented in the current POM. Nevertheless, such technologies come with additional capital investment and operating costs that may outweigh the profit generated. Therefore, in this work, a systematic approach is presented to synthesise the palm oil milling processes with oil recovery technologies which is technically and economically feasible.

Keywords Palm oil mill · Process synthesis · Process optimisation
Oil recovery technologies

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Nomenclature

Abbreviation	Description
AOT	Annual Operational Time
CPO	Crude Palm Oil
CPKO	Crude Palm Kernel Oil
DC	Decanter Cake
DOE	Department of Environment
EFB	Empty Fruit Bunch
FFB	Fresh Fruit Bunch
L	Oil Loss
LPS	Low Pressure Steam
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MPOB	Malaysian Palm Oil Board
MPS	Medium Pressure Steam
MT	Metric Tonne
PEFB	Pressed Empty Fruit Bunch
PK	Palm Kernel
PKS	Palm Kernel Shell
POM	Palm Oil Mill
POME	Palm Oil Mill Effluent
PPF	Palm Pressed Fibre
PSE	Process Systems Engineering
R	Oil Recovery
X	Mass Conversion

Sets	Description
e	Index for electricity
i	Index for feedstocks
j	Index for technologies at level j
j'	Index for technologies at level j'
p	Index for intermediate products
p'	Index for final products
u	Index for utility

Variables	Description
B_j	Binary variable denoting the existence of technology j
$B_{j'}$	Binary variable denoting the existence of technology j'
CRF	Capital recovery factor
$CAPEX$	Total capital cost
E_e^{Con}	Total electricity consumption
E_e^{Demand}	Total electricity demand
EP	Economic performance
F_{LPS}^{Con}	Total flowrate of low pressure steam

F_{MPS}^{Con}	Total flowrate of medium pressure steam
F_{u}^{Con}	Total flowrate of utilities
F_{water}^{Con}	Total flowrate of utility water
F_{u}^{Demand}	Total utility demand
F_{j}^{Design}	Design capacity of technology j
$F_{j'}^{\mathrm{Design}}$	Design capacity of technology j'
F_{ij}	Flowrate of feedstock i to technology j
$F_{j'p'}$	Flowrate of final product p' from technology j'
F_{jp}	Flowrate of intermediate product p from technology j
F_{p}	Flowrate of intermediate products p
$F_{p'}$	Flowrate of final products p'
$F_{pj'}$	Flowrate of intermediate products p to technology j'
F_{PL}	Total flowrate of pressed liquid
F_{SFB}	Total flowrate of sterilised fruit bunch
GP	Total gross profit
O_{i}	Oil content of feedstock i
O_{p}	Oil content of intermediate product p
$O_{p'}$	Oil content of final product p'
$OPEX$	Total operating cost
OP_{p}	Oil percentage of intermediate product p
$OP_{p'}$	Oil percentage of final product p'
z_{j}	Number of units of technology j selected
$z_{j'}$	Number of units of technology j' selected

Parameters	**Description**
C_{e}	Cost of electricity e
C_{i}	Cost of feedstock i
C_{u}	Cost of utility u
$\mathrm{C}_{p'}$	Cost of final product p'
CC_{j}	Capital cost for technology j
$\mathrm{CC}_{j'}$	Capital cost for technology j'
F_{i}	Flowrate of feedstock i
L_{ijp}	Percentage oil loss technology j
$\mathrm{L}_{pj'p'}$	Percentage oil loss technology j'
OC_{j}	Operating cost for technology j
$\mathrm{OC}_{j'}$	Operating cost for technology j'
OP_{i}	Oil percentage of feedstock i
r	Discount rate
R_{ijp}	Percentage oil recovery technology j
$\mathrm{R}_{pj'p'}$	Percentage oil recovery technology j'
$\mathrm{t}_{k}^{\max}$	Operational lifespan
U_{ujp}	Utility specification of intermediate product p for technology j
$\mathrm{U}_{uj'p'}$	Utility specification of final product p' for technology j'
X_{ijp}	Component mass conversion of feedstock i
$\mathrm{X}_{pj'p'}$	Component mass conversion of intermediate product p

Y_{ej}	Electricity consumption rate per unit of technology j
$Y_{ej'}$	Electricity consumption rate per unit of technology j'
$Y_{ej'p'}$	Electricity consumption rate of technology j' per unit of final product p' produced
Y_{ejp}	Electricity consumption rate of technology j per unit of intermediate product p produced

1 Introduction

Over the past few decades, palm oil industry has expanded dramatically as one of the major oils and fats providers for global needs. In year 2016, palm oil contributes up to 30% of oils and fats production globally [39]. As reported by American Soybean Association [60], palm oil accounts for 68.9 million metric tonnes (MT) out of 203 million MT of vegetable oils consumed worldwide (contributed to 34%). Note that more than 20 million MT of crude palm oil (CPO) are produced annually in Malaysia [34], making Malaysia the second largest producer and exporter of palm oil products after Indonesia. As the second largest producer and exporter of CPO, Malaysia plays an important role in fulfilling the growing global need for oils and fats sustainability.

In the palm oil industry, fresh fruit bunch (FFB) is first harvested in oil palm plantation and sent to palm oil mill (POM) to produce CPO. On the other hand, the generated palm kernel (PK) is sent to kernel crushing plant for production of crude palm kernel oil (CPKO). During the milling process, by-products, such as palm pressed fibre (PPF), palm kernel shell (PKS), emptyfruit bunch (EFB), decanter cake (DC) and palm oil mill effluent (POME) are generated. Both CPO and CPKO will be further refined into various products (e.g. edible oil, stearine, lubricant, etc.) in refinery. A major issue found in the POM is the low oil recovery (or high oil lost) during milling process. To address this issue, various technologies such as tilted steriliser, double screw press, vacuum clarifier, etc. have been developed. However, such technologies come with additional capital investment and operating costs. Therefore, a study to trade-off between increments in oil yield with costs is necessary. Besides, the total oil balance of the entire milling process based on the input of oil in FFB and output of oil from the milling process has yet to be studied. Hence, there is a need to develop a systematic approach for flowsheet synthesis and optimisation of palm oil milling process with maximum oil recovery.

In the following sections, systematic approaches for flowsheet synthesis are first reviewed. In Sect. 2, a problem statement for this work is presented, followed by the development in palm oil milling processes in Sect. 3. A detailed formulation for material balance, utility balance and economic analysis is given in Sect. 4. Next, a typical palm oil milling process in Malaysia is synthesised and optimised based on the proposed framework in Sect. 5. Lastly, a conclusion of this work is drawn and given at the end of this chapter.

1.1 Systematic Approach for Flowsheet Synthesis

Various process synthesis tools have been established to design chemical processes in the industry [23, 58]. Nishida et al. [43] defined process design as the *selection of a particular interconnection of processing systems which meet certain constraints out of a large number of alternatives*. A flowsheet is the optimal interconnection of processing systems as well as the optimal type and design of the units within a process system [17]. *Process Systems Engineering* (PSE) is a field in which systematic computer-based approaches are developed to synthesise a flowsheet [53]. Various approaches have been developed to provide a methodological framework in designing chemical processes [57].

Conventionally, flowsheet synthesis is carried out in a hierarchical approach which is divided into three distinct levels, namely synthesis optimisation, design optimisation and operational optimisation, to be solved in sequence [15]. The hierarchical approach is well recognised in the field of process synthesis [12, 11]. The onion model is proposed as a hierarchical decision-making tool for process synthesis [30, 56]. Following that, hierarchical approach has been used in various studies for the synthesis of wastewater treatment [16], thermal [37], biorefinery [42, 52] and chlor-alkali production systems [55], etc. On the other hand, mathematical programming approaches were developed for flowsheet synthesis by screening a wide range of possible flowsheet alternatives under any possible circumstance. As shown in the literature, many mathematical optimisation approaches for flowsheet synthesis have been presented. For instance, Grossmann and Santibanez [19] presented a mixed-integer linear programming (MILP) model for flowsheet synthesis. Biegler et al. [4] developed an alternative MILP model for flowsheet synthesis with consideration of mass and energy balances, equipment sizing and costing, economic evaluation, process simulation and optimisation. Besides, various mathematical optimisation models have been developed to synthesise water network [27], trigeneration [32, 62], biorefinery [28, 41], hydrocarbon biorefineries [61], industrial symbiosis [40], biomass trigeneration [2, 3], biogas systems [46], etc.

Most papers discussed earlier focused on integrated biorefinery, resources network or energy systems in which water and energy (i.e. heat and electricity) consumptions are used as the major parameter in the optimisation models. However, it is noted that limited of these works discussed on the synthesis of POM flowsheet. Recently, Foong et al. [14] presented a systematic approach to synthesise palm oil milling process. CPO serves as the main product and income generator in a POM. With respect to that, it is essential to trace the oil content across the flowsheet synthesised which has not been done in the previous research works. The optimal technology selection for FFB processing with consideration of oil content, energy consumptions, process capacity and their respective economic interests shall be performed. With respect to this, it is essential to develop a systematic approach to synthesise and optimise a milling process with maximum oil recovery. To illustrate the proposed approach, a typical palm oil milling process case study in Malaysia is solved.

2 Problem Statement

Due to the variety in established technologies available in market, the synthesis of an optimal POM configuration is highly complicated. A simplified generic graphical representation of model is shown in Fig. 1. The synthesis problem addressed is stated as follows. The feedstock i with given flowrate of F_i (in this case, FFB is the only feedstock) can be converted to intermediate product $p \in P$ (e.g. sterilised fruit bunch, F_{SFB}, pressed liquid, F_{PL}, etc.) through technology $j \in J$. Intermediate product p can then be further converted to final product $p' \in P'$ (e.g. CPO and PK) via technology $j' \in J'$. By-products (e.g. PKS, PPF, DC, etc.) are represented as a form of intermediate product p or final product p' in the model. The oil content of feedstock i, intermediate product p and final product p' are defined as O_i, O_p and $O_{p'}$ respectively. Note that every technology $j \in J$ and $j' \in J'$ may have more than one inlet and outlet stream, allowing every stream to merge or split, depending on constraints set on the model. Besides, intermediate product p can also be taken as final product p' if it could be sold directly. The mass conversion (X), oil loss (L) and oil recovery (R) of technology j from feedstock i and technology j' from intermediate product p are specified as X_{ijp}, $X_{pj'p'}$, L_{ijp}, $L_{pj'p'}$ R_{ijp} and $R_{pj'p'}$ respectively. Meanwhile, utility consumption F_u^{Con} (e.g. low pressure steam, F_{LPS}^{Con}, medium pressure steam, F_{MPS}^{Con} and utility water, F_{water}^{Con}) and electricity consumption E_e^{Con} for the entire mill are specified as U_{ujp}, Y_{ejp} for technology j and $U_{uj'p'}$, $Y_{ej'p'}$ for technology j'.

In this work, the objective is to develop a systematic approach, generating an optimal and robust POM configuration with maximum economic performance (*EP*). The oil loss and oil recovery in every technologies $j \in J$ and $j' \in J'$ will be traced accordingly. Usually, the available equipment in the market have a fixed design capacity of technology j (F_j^{Design}) and j' ($F_{j'}^{Design}$); therefore, the proposed approach will determine the number of units required for technologies j and j' selected, represented by z_j and $z_{j'}$ respectively. The total capital cost, *CAPEX* and total operating cost, *OPEX* can be calculated based on the costs of selected technologies j and j' (CC_j, $CC_{j'}$, OC_j and $OC_{j'}$). The following section provides a better insight on the process in which the development of palm oil milling technologies will be discussed in detail.

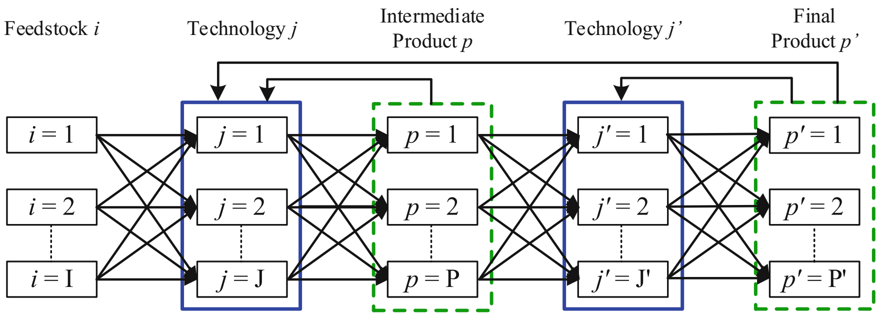

Fig. 1 Generic representation of superstructure for scenarios [14]

3 Development in Palm Oil Milling Processes

Figure 2 shows a typical process flow diagram of palm oil milling process. As shown, the process can be generally divided into several unit operations. Firstly, FFB is sterilised to ease the separation of fruitlets and EFB. Most of the POMs in Malaysia are using horizontal cylindrical vessels with three bar steams for sterilisation process [49]. Since the last decade, continuous steriliser [26] and tilting steriliser [31] were introduced to improve milling efficiency by lowering labour and maintenance cost. However, the capital cost of the new type of steriliser is higher comparing to the conventional horizontal steriliser. Depending on the type of sterilisation technology and availability of steam, several sterilisation patterns from single- to triple-peak steam cycles are practised [13]. By using different patterns of sterilisation process, the oil yield will be improved. Upon sterilisation, the fruitlets and EFB are threshed via rotating or fixed drum equipped with rotary beater bars [9]. Meanwhile, POME and EFB are generated in sterilisation and threshing process respectively.

The separated fruitlets, which consist of palm nuts and mesocarp fibres, are then sent to the digestion process. Under the high-pressure condition in a steam-jacket drum, fruitlets will be digested in which oil is released through the rupture of oil-

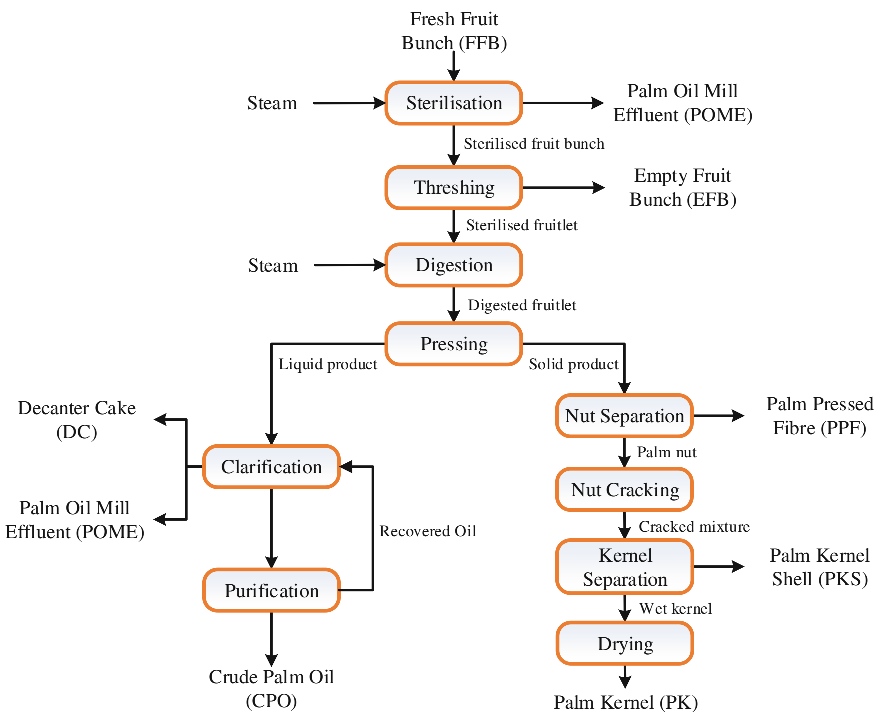

Fig. 2 Typical palm oil mill processing unit operations [14]

bearing cells [49]. Next, the digested fruitlets go through a pressing system to squeeze out the oil from mesocarp fibres in the fruitlets. Mechanical screw press is commonly used in the pressing process. Double screw press with twin screws rotating in opposite directions was introduced to increase the pressing efficiency [47]. Due to its larger capacity and shorter processing time, double screw press is favourable in the milling industry [22]. During the pressing process, solid and liquid products are generated. The solid product consists of a mixture of mesocarp fibres and palm nuts. Meanwhile, a mixture of water (45–55%), palm oil (35–45%) and fibrous materials are also produced [8].

For the solid products, the fibres and palm nuts can be separated via inclined rotary separator [45], or depericarper which based on air floatation concept [20]. Maycock [38] introduced ripple mill cracker where the palm nuts were cracked and air cyclone is used to remove the dust particles of the cracked mixture [24]. The cracked mixture from the palm nuts, which consist of PK and PKS is separated via clay bath or hydrocyclone based on the difference in specific gravity [21]. Meanwhile, a new cracking process known as Rolek nut cracker [50], followed by a multiple-staged winnowing system [51] with higher efficiency were introduced.

To improve the removal efficiency of the entrained impurities (water and fibrous materials) from the oil, hot water is added in clarification tank [49]. Jorgensen and Singh [25] proposed to combine a two-phase decanter with a rotate drum drier to reduce the amount of water needed. Recently, three-phase decanter is introduced to replace clarification tank and sludge centrifuge [1]. In this process, the entrained solid particles are removed as DC while water is removed as POME. The oil is then further purified into CPO through centrifugal and drying operations. In order to minimise deterioration in oil quality, the purified CPO must be stored between 32 and 40 °C [6].

Based on above discussion, it is noted that there are many alternative technologies that can be used to improve the overall efficiency of POM. Note also that throughout the milling process, various by-products are generated with oil being trapped and remains unrecovered. For example, 10.6 g/L of oil and grease were trapped in POME [5]. Meanwhile, EFB and PPF contains approximate 3–4% [18] and 1.8–3.96% [59] (wet basis) of residual oil respectively. According to [7], an estimation of 10% oil lost across multiple unit operations in the milling process. Therefore, oil loss is a critical issue in POM as it causes a significant impact on the economic performance of POMs. To overcome this issue, various research and development works were conducted to recover the oil from by-products. For instance, EFB screw press and three-phase decanter were introduced to recover oil from EFB and improve the overall oil extraction efficiency. However, most technology providers only focused on individual equipment or process. The oil balance for the entire milling processes is not being assessed. Hence, this is the subject of this work. It is important to synthesis and optimise the entire milling process simultaneously to maximise oil recovery in POM, thus achieving a greater economic performance. Material and energy flows of the entire process as well as expected productivity of the developed POM flowsheet can be determined. Based on the proposed approach, aspects such as process synthesis (e.g. system configuration and technology selection) and design optimisation (e.g. capacity, number of units) within the milling process can also be identified.