PROCESS DEVELOPMENT AND DESIGN OF AN INTEGRATED PALM OIL PROCESSING PLANT

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ABSTRACT

The palm oil industry is one of the most profitable and significant contributors to Malaysia's economy. However, recently, the European Union is banning Malaysia's palm oil due to its environmental impact. Hence, it is urgent to improve Malaysia's palm oil industry system to reduce the impact on the environment by integrating the stand-alone palm oil process as integration of a process proven to enhance overall process performance (process efficiency, profitability and environmental sustainability). An Integrated Palm Oil Processing Plant is expected to increase the productivity and sustainability performance of palm oil production while reducing the overall cost of the process. To date, the integration of the processes specifically on the crude palm oil (CPO) products and derivatives has not been executed or academically researched. This study focused on the process design and development for integration of processes that involve the main product from the upstream of palm oil industry, CPO. Process selection for the integration was based on the material integration of CPO processing flow from milling (extraction of CPO) to refinery and dry fractionation (refining and separation of palm olein and stearin), hydrogenation of palm stearin, and fractionation of the hydrogenated palm stearin. Mass balance and process simulation was done to evaluate the mass throughput for stand-alone palm oil processes as the basis for scale up of the current (stand-alone plant) capacity to the proposed integrated plants to meet the hydrogenated palm stearin capacity process of 550 MT/day, 225 MT/day, and 100 MT/day. The feasibility of the integrated plant was analysed based on economic potential and sustainability performance. In terms of economic, the Integrated Palm Oil Processing Plant with the largest capacity (550 MT/day) was found to be feasible based on the profitability analysis where it has the highest return on investment (ROI) of 173% as compared to ROI of 85% and 49% for the other integrated plant capacity in comparison, 225 MT/day and 100 MT/day. In terms of sustainability, the integrated plant was compared with existing stand-alone plants using the modified palm oil milling sustainability index where the largest capacity (550 MT/day) of the integrated plant showed the highest overall score of 79 for the sustainability index, which indicated an improvement in the sustainability performance. For validation of the integrated plant, opinions from subject matter expert were obtained from the industry experts that include plant managers and engineers, project manager and academician. The experts' opinions on the integrated plant were varied in terms of the integrated plant management (control system, waste management and data management), operational (plant maintenance, utilities, operators, and technical staff) and sustainability (waste production, gas emissions and transportation). In summary, based on their feedback, the concept of an integrated plant was found to be promising in terms of systematic management, operational reliability, and support sustainable goals. In conclusion, the integrated plant with the largest capacity of 550 ton palm stearin hydrogenated fatty acids per day yielded a promising ROI, a great profit margin, and better sustainable performance and based on experts' opinion, the integrated plant concept has the prospect for a more efficient and reliable plant, proving that integration of palm oil processes is feasible in terms of productivity, economic potential and sustainability of the industry.

ABSTRAK

Industri minyak sawit ialah salah satu penyumbang penting dan menguntungkan kepada ekonomi Malaysia. Bagaimanapun, Kesatuan Eropah baru-baru ini mengharamkan minyak sawit Malaysia kerana kesannya terhadap alam sekitar. Oleh itu, adalah penting untuk menambah baik sistem industri minyak sawit Malaysia bagi mengurangkan kesan terhadap alam sekitar dengan menyepadukan proses minyak sawit yang berdiri sendiri kerana penyepaduan proses telah terbukti meningkatkan prestasi keseluruhan proses (kecekapan proses, keuntungan dan kelestarian alam sekitar). Loji Pemprosesan Minyak Sawit Bersepadu dijangka boleh meningkatkan produktiviti dan prestasi kemampanan pengeluaran minyak sawit sambil mengurangkan kos keseluruhan proses tersebut. Sehingga kini, penyepaduan proses khususnya pada produk dan terbitan minyak sawit mentah (CPO) belum dilaksanakan atau dikaji secara akademik. Kajian ini memfokuskan kepada reka bentuk proses dan pembangunan untuk penyepaduan proses yang melibatkan produk utama daripada permulaan industri minyak sawit iaitu CPO. Pemilihan proses untuk penyepaduan adalah berdasarkan penyepaduan bahan aliran pemprosesan CPO daripada pengilangan (pengekstrakan CPO) kepada penapisan dan pecahan kering (penapisan dan pengasingan olein dan stearin sawit), penghidrogenan stearin sawit, dan pemecahan stearin sawit terhidrogen. Imbangan jisim dan simulasi proses telah dilakukan untuk menilai daya pemprosesan jisim bagi proses minyak sawit berdiri sendiri sebagai asas peningkatan kapasiti semasa (loji berdiri sendiri) kepada loji bersepadu yang dicadangkan untuk memenuhi proses kapasiti stearin sawit terhidrogen 550 MT/hari, 225 MT/hari, dan 100 MT/hari. Kebolehlaksanaan loji bersepadu dianalisis berdasarkan potensi ekonomi dan prestasi kemampanan. Dari segi ekonomi, Loji Pemprosesan Minyak Sawit Bersepadu dengan kapasiti terbesar (550 MT/hari) didapati boleh dilaksanakan berdasarkan analisis keuntungan yang mempunyai pulangan pelaburan (ROI) tertinggi sebanyak 173% berbanding ROI sebanyak 85% dan 49% untuk kapasiti loji bersepadu lain dalam perbandingan, 225 MT/hari dan 100 MT/hari. Dari segi kemampanan, loji bersepadu itu dibandingkan dengan loji bersendirian sedia ada menggunakan indeks kemampanan pengilangan minyak sawit yang diubah suai di mana kapasiti terbesar (550 MT/hari) loji bersepadu menunjukkan skor keseluruhan tertinggi iaitu 79 untuk indeks kemampanan, yang menunjukkan peningkatan dalam prestasi kemampanan. Untuk pengesahan loji bersepadu, pendapat pakar subjek diperoleh daripada pakar industri termasuk pengurus dan jurutera loji, pengurus projek dan ahli akademik. Pendapat pakar mengenai loji bersepadu adalah berbeza dari segi pengurusan loji bersepadu (sistem kawalan, pengurusan sisa dan pengurusan data), operasi (penyelenggaraan loji, utiliti, operator dan kakitangan teknikal) dan kemampanan (pengeluaran sisa, pelepasan gas dan pengangkutan). Secara ringkas, berdasarkan maklum balas responden, konsep loji bersepadu berpotensi dari segi pengurusan yang sistematik, keandalan operasi dan sokongan matlamat yang mampan. Kesimpulannya, loji bersepadu dengan kapasiti terbesar 550 tan lemak asid stearin sawit terhidrogen sehari menghasilkan ROI yang berpotensi, margin keuntungan yang besar, dan prestasi mampan yang lebih baik. Berdasarkan pendapat pakar, konsep loji bersepadu mempunyai prospek sebagai loji yang lebih cekap dan andal, membuktikan bahawa penyepaduan proses minyak sawit boleh dilaksanakan dari segi produktiviti, potensi ekonomi dan kemampanan industri.

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LIST OF ABBREVIATIONS

CO	-	Cooking Oil
CPKO	-	Crude Palm Kernel Oil
CPL	-	Crude Palm Olein
CPO	-	Crude Palm Oil
CPS	-	Crude Palm Stearin
PFAD	-	Palm Fatty Acid Distillates
PKC	-	Palm Kernel Cake
PMF	-	Palm Mid Fraction
PO	-	Palm Oil
POI	-	Palm Oil Industry
PSO	-	Particle Swarm Optimization
POPC	-	Palm Oil Processing Complex
PSTHFA	-	Palm Stearin Hydrogenated Fatty Acids
RBD	-	Refined Bleached Deodorized
RBD PL	-	Refined Bleached Deodorized Palm Olein
RBD PO	-	Refined Bleached Deodorized Palm Oil
RBD PS	-	Refined Bleached Deodorized Palm Stearin

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CHAPTER 1

INTRODUCTION

This chapter provides an outlook on the global and local production of the palm oil industry and an overview of the current issues in the palm oil industry, followed by the research background and problem statement of the research. From the problem statement, the research objectives will be outlined, and the scope of the study related to the development and analysis of the integrated system of palm oil processes is described. Finally, at the end of the chapter, the critical contributions of this thesis that are relevant to the research field and integration system of the palm oil processes are then being highlighted.

1.1 Overview

Palm oil has been appraised as a wonder crop because of its efficiency and versatility. Oil palm generates the highest production of vegetable oil per hectare of land and can be used as an input for varieties of products (Sayer *et al.*, 2012). Khatun *et al.* (2017) has listed the uses of oil palm in many categories, namely food, oleochemicals, and biofuels. For food, oil palm is made into cooking oil, industrial frying fat, margarine, vegetable ghee, confectionery fat, ice cream, non-dairy cream, salad dressing, cheese analogues, chocolates, supplements, and vitamins. While in the processes of oleochemicals, it is used as input to produce surfactant, personal care products, cosmetics, agrochemicals, lubricants, toilet soap, industrial cleaning, printing ink, polyols, and polyurethane. Recent uses of oil palm are as biofuels such as biodiesel, jet fuel, and biogas.

According to Ritchie and Roser (2021), a rapid increase of palm oil production has been seen for over 50 years, from just only 2 million tonnes in 1970 and 71 million tonnes in 2018, an increase of more than 35 times higher. The high production of palm oil is due to the increasing demand for oil palm because of population growth, especially in developing countries. Hence, the production is expected to reach 78 million tonnes by 2020, which is expected to cause the expansion of palm plantations (Khatun, Moniruzzaman, *et al.*, 2017). However, the latest Annual Report 2020 by MPOC stated that the world's palm oil production is recorded at 74 million tonnes which accounted for 31.4% of world oils and fats production in 2020 (Malaysian Palm Oil Council, 2022) while in recent years of 2021, the world's palm oil production was reported a total of 73 million tonnes (Shahbandeh, 2022).

In response to the increasing demand, under the collective efforts by the Malaysian Palm Oil Board (MPOB) and Malaysian Palm Oil Council (MPOC), the oil palm planted area has expanded significantly, from a mere 55 000 hectares in 1960 (Nambiappan *et al.*, 2018) to a 5.74 million hectares as of 2021 (Malaysian Palm Oil Board, 2021). In tandem with the area expansion, the production of palm oil also grew significantly from less than 100 000 tonnes in 1960 to about 17.32 million tonnes in 2016, which consequently led to the increase in the number of mills in Malaysia from 261 palm oil mills in operation with a processing capacity of 42.9 million tonnes of fresh fruit bunches (FFB) per year in 1990, to 453 mills with a total capacity of 110.3 million tonnes per year in 2016 (Norhidayu *et al.*, 2017). In addition, the downstream process, which includes refining and fractionation of palm oil and palm kernel oil, has also been expanded from just merely 10% of Malaysia's total CPO being refined in 1974 to a game-changer in the marketing pattern and export of Malaysia palm oil products that are readily available as processed palm oil products, which includes refined, bleached and deodorized (RBD) palm oil products and palm oil and its fractions which are virtually free from trans-fatty acids and thus, a natural replacement for hydrogenated vegetable oils and fats (PORAM, 2019).

In place of that development, the Malaysian oil palm industry has been transformed to become one of the key contributors to Malaysia's Gross Domestic Product (GDP), foreign exchange earnings, and the creation of employment opportunities. On average, the industry contributes 5% to 7% of the country's GDP, with export revenue for the last five years averaging at RM 64.24 billion annually

(Nambiappan *et al.*, 2018). This has been confirmed by Ahmad Parveez and Fauziah (2020), which stated that the export revenue of total palm products for 2019 was RM64.84 billion. This revenue results from the exports of oil palm products in 2019, amounting to 27.86 million tonnes, where 18.47 million tonnes are of palm oil (Malaysia Palm Oil Council, 2020, Economics & Industry Development Division, 2019 & Ahmad Parveez and Fauziah, 2020). Since 2010, the palm oil industry has been identified as one of the areas under the 12 National Key Economic Areas (NKEA) where the palm oil sector is aimed at improving upstream productivity and increasing downstream expansion while focusing on the sustainable development of the oil palm industry (May, 2012). However, despite attaining significant achievements in both its palm oil production and exports, Malaysia is currently facing several issues (Nambiappan *et al.*, 2018). Among the problems are due to intense pressure exerted by non-governmental organizations (NGO) on matters of environment and other negative allegations against the palm oil industry. Hence, a continuous effort in branding palm oil as an environmentally sustainable palm oil through adopting Malaysian sustainable palm oil throughout the value chain is deemed the game-changer for the industry in the future (Nambiappan *et al.*, 2018).

In Malaysia, the palm oil industry is divided into four main divisions, namely, upstream (harvesting and milling), midstream (trading and crude palm oil bulking), downstream (refining, fractionation, oleochemical, esterification, and refined product storage), and consumer products (packaging and branding) (Sime Darby Plantation, 2009). Hence, to embrace the government's effort under NKEA, several studies have been conducted related to improving sustainability in palm oil manufacturing, focusing on the area of environmental impacts of palm oil production, renewable energy applications of palm oil, utilization of palm oil waste, and sustainable development and practices (Abdullah *et al.*, 2015). In addition, another opportunity towards sustainability has also been explored that involves process integration. Among those opportunities research includes the integrated palm biodiesel production that is economically viable (May *et al.*, 2009), integrated palm oil-based biorefinery with an existing palm oil mill, and palm oil refinery with optimum combined heat and power (CHP) (Kasivisvanathan *et al.*, 2012 and Ng and Ng, 2013), integrated CPO and PKO mills that lead to energy efficiency (Aziz *et al.*, 2015) and integrated POME-derived biogas utilization that is distributed for use at multiple palm oil mill clusters (Theo, Jeng Shiun Lim, *et al.*, 2017). These abovementioned researches that have been conducted shows that recent researchers are now going towards sustainable production of palm oil products and derivatives through the integration of processes that enhance the overall process performance in terms of efficiency, profitability, and environmental sustainability (Ng and Ng, 2013), improve economic performance, use of environmentally friendly waste material and simplification of waste management (Aziz *et al.*, 2015).

As a continuity of the effort towards sustainable production of the palm oil industry in Malaysia, this research is intended to explore the conceptual integrated palm oil processing from upstream to the downstream process of palm oil and palm oil derivative products. This integrated palm oil processing plant is developed and analyzed to merge and integrate the material flow of the milling, refining, fractionation, and hydrogenation process, with the focus of the main product in palm oil industry, the crude palm oil (CPO), in one processing facility, into a target production, based on the current market demand of palm oil products. This integrated processing plant is expected to reduce the impact of the palm oil industry on the environment, in terms of boiler fuel combustion and the transport of materials, a potential for the reduction of GHG, and reduction of material loss in the production process which will increase cost efficiencies and additional savings through material flow network. This research will then evaluate the integrated processing complex's economic viability and sustainability performance to measure its feasibility.

1.2 Problem Statement

According to an article by Sime Darby Plantation (2009), the palm oil value chain can be divided into four main divisions: upstream, midstream, downstream processing, and consumer products. Current practice is the upstream that involves harvesting and milling process, usually are performed within the plantation itself. This is as according to Narodoslawsky (2003), due to the decentralization of the raw material (e.g., fresh palm fruit bunch) to the milling plant, which in turn requires certain effort to collect them, hence making this kind of agricultural-sourced raw material need to be close to its sources. While the upstream chain is isolated near or inside the plantation itself, the processing of oil palm FFB results in the production of wastes in the form of POME, EFB, mesocarp fiber, and shell. POME is generated primarily from oil extraction, washing, and cleaning processes that contain cellulosic material, fat, oil, and grease, which may cause substantial environmental problems (Abdullah and Sulaiman, 2013; Abdullah *et al.*, 2015). For midstream, the activities defined in this chain are trading and crude palm oil bulking. For CPO trading, the CPO is exported through liquid bulking facilities, while the palm kernel cake is commonly exported in the form of dry bulk (Zulhusni and Nordin, 2006). For this stream, no processing is involved, but transportation via tanker is taking place to the bulking facilities and refinery. As mentioned by Arshad *et al.* (2019), transportation is an essential component in the palm oil supply chain. However, transportation is also one of the primary sources of greenhouse gas (GHG) emitted from the burning of fossil fuels. Downstream activities include refining, fractionation, oleochemical, esterification, and refined product storage. The downstream processes such as refining, fractionation, and oleochemical are commonly located in one processing facility. The downstream process in the palm oil industry (e.g., refining and fractionation), which shares the same features as conventional fossil and mineral raw materials, follow the economy of scale principle where it indicates that larger plants will have lower production costs (Narodoslawsky, 2003). Therefore, in current practice, bigger plants have been built to cater to the integration of refining and fractionation process of palm oil products, including packaging. While for oleochemical, the plant is usually in an integrated complex with a diversity of unit production to produce diversified oleo products. The most significant environmental problem resulting from refining was crude palm oil (CPO) and, consequently, refined palm oil (RPO) for fractionation to produce refined palm and palm stearin. This was followed by boiler fuel combustion and the transport of materials into the processing facilities, suggesting that a potential mitigation measure for the reduction of GHG is needed to reduce the GHG from the downstream activities.

Therefore, despite the enormous potential of the palm oil industry in Malaysia, the issues mentioned above are considered to have a significant impact in the bid to its importance, especially in context of environmental issues where, environmentalists acknowledge palm oil as cruel oil (Ferdous Alam *et al.*, , 2015 and

Khatun, Reza, *et al.*, 2017). Therefore, it is critical to ensure that the palm oil industry could overcome such stigma. This could be done by re-designing the palm oil production process, that are more sustainable based on the pillar of sustainable development, that is economy, environment, and society (Khatun, Reza, *et al.*, 2017). El-Halwagi (2017) defined the sustainable design of industrial processes as "design activities that lead to economic growth, environmental protection, and social progress for the current generation without compromising the potential of future generations to have an ecosystem that meets their needs". According to him, process integration is the enabling tool to attain sustainability to methodically and effectively achieve the objectives of a sustainable design (El-Halwagi, 2017).

For insights, various benefits of integrating the processes have been observed in other industries; for instance, study by De Oliveira Magalhães (2009), showed that the integration of refinery operations and production of petrochemicals can lead to a framework that adds value for both businesses. Substantial savings can be achieved, either for existing plants or new ones, by properly designing and/or operating a refinery and a petrochemical plant. These savings are derived from sharing common infrastructure (tank farm, utilities, terminals, pipeline), leading to a reduction in capital investments or reduced inventories and energy/utility requirements if both sites are close enough to benefit from an integrated operation (De Oliveira Magalhães, 2009). AMEC Earth & Environmental (2007), for example, has conducted a study on the environmental benefits of industrial integration. In the study, they established a comparison of standalone facilities with the conceptual design of the integrated complex (that consists of a combination of standalone facilities in the hydrocarbon industry, namely upgrader, refinery, and petrochemical). The findings were, in terms of air emission and water demand, the standalone facilities range from 1.5 to 5.1 times and 1.1 to 1.6 times greater than integrated complex, respectively. In contrast, for footprint comparison, standalone facilities occupy 1.4 to 2.2 times the area of integrated complex (AMEC Earth & Environmental, 2007).

Hence, for a few years now, there has been an emphasis for a change from standalone operations towards the integrated manufacturing facility. For palm oil-based industry, several studies have been done related to integration of process, for example, in the biodiesel palm oil-based industry, where integrated palm oil biodiesel and its downstream product has been successfully tested on a pilot scale, and is currently widely commercialized and has been quoted as economically viable and makes the palm biodiesel plant to be able to stand alone (May et al., 2009). Other works by Ng *et al.* (2013) have proposed the concept of material exchange between a palm oil-based biorefinery integrated with an existing palm oil mill, palm oil refinery and combined heat and power (CHP) system as individual blocks which enhance the overall process performance in terms of efficiency, profitability, and environmental sustainability. A Palm Oil Industrial Cluster (POIC) that will facilitate the upstream and downstream process of the palm oil industries also has been proposed by East Coast Economic Region Development Council (2010). Other recent study by Tan *et al.* (2020) where they consider the retrofitting of an existing palm oil mill into a methane avoidance palm oil based-complex (POBC) as well as integrating its palm oil refining producing olein and stearin, and palm fatty acid as by-products, focusing on using the mixed integer linear programming model to optimise the POBC configuration of and investigate the economic feasibility of POME elimination approach (Tan *et al.*, 2020). Foong and Ng (2022) also has working on systematic synthesis and optimization of the oil palm value chain (OPVC) including oil palm plantation (OPP), processing (POM, kernel crushing plant (KCP), and palm oil refinery (POR)), and supply chain (consumer and transportation). The scope of OPVC network in this study is from different supply chain management and is measured in terms of the number of interconnectivity among stakeholders (Foong and Ng, 2022). Hence, nowadays, with good accessibility to plantations, milling, downstream technologies, and related industries, there is a rapid growth in publications from researchers based at Malaysian universities. The palm oil industry-related research has been done vastly on technological development related to the palm oil industry and sustainability issues (Balle *et al.*, 2015).

However, to date, most of the current processes of palm oil are standalone processes from different plants owned by different companies and located at different locations. Begum *et al.* (2019) has quantified that as of 2017, there are 454 mills, 53 refineries, and 19 oleochemical plants that are currently operating in Malaysia. By logic, integration of palm oil processes in the palm oil industry should have been getting quite the attention. It is evident that products from each stage of production, per se; the raw fruit bunch from the plantation to the milling process and the crude palm oil (CPO) from the milling to the refinery process; which shows that integrating the process will reduce the transportation cost of the feedstock in the process if it is adjacently located to each other, as well as other benefits of sustainable operation. The studies mentioned earlier has shown interest on integration of processes in palm oil industry. These studies, however, are mainly related to the industrial symbiosis that involves multiple processing facilities owned by different companies that have potential benefits from process integration and combined heat and power (CHP) integration rather than a process design and development based. The integrated manufacturing facility which intended to facilitate a complete range of value-added products from the raw fruits/seeds to consumers' usage, however, is making the standalone operations/ processing facility become more dependent on each other, and any of their action will impact the whole process (Anderson, 2005 in Shahidi, 2005). Furthermore, the latest studies by Foong and Ng (2022) has noted that the allocation of materials from and to multiple sites with the presence of various organisations in the industry will further complicates the supply chain network.

Therefore, this research is intended to develop and design an integrated palm oil processing plant, as one unit of manufacturing facility, that includes the processes from upstream to downstream production of palm oil processes, that are currently exists as a standalone. Currently, to design the integrated plant, a lot of technical data is not readily unavailable for design consideration and technical design data. Hence, it is to be obtained through manual calculation and process simulation. The data extracted shall be validated in terms of their technicality, productivity, and profitability. This is to ensure that the technical capability and the proposed design are working and support the commercial value. The resulting technical knowledge on the design can be estimated in piloting scale to ensure it is a technically sound design that contributes to safety and sustainability, up to par with the more complex integrated chemical plant. In terms of commercialization, the study will include the economic evaluation to convince the investors regarding the integrated palm oil processing plant (upstream, midstream, and downstream).

1.3 Research Objectives

This research aims to develop a new conceptual integrated palm oil processing complex from upstream to the downstream process of palm oil and palm oil derivatives products. The sub-objectives to obtain the main objectives includes:

(a) To define the separated process plant and develop it into a conceptual integrated processing complex.

(b) To design and configure the conceptual integrated processing complex based on plant capacity, raw materials input, and target production.

(c) To evaluate the proposed integrated palm oil processing plant based on economic potential using plant design economic evaluation method and sustainability performance using palm oil mill sustainability index (POMSI)).

1.4 Scope of Research

The scope of the research is to achieve the sub-objectives. To achieve sub-objective (a), the scope of research includes:

(a) Analysing the process development and design for plant design of chemical process industry to be adopted in the palm oil industry.

(b) Identifying and selecting the current technologies of the upstream (milling), midstream (refining), and downstream (hydrogenation and fractionation) processes in the palm oil industry.

(c) Developing the integrated palm oil processes based on material flows from all selected processes in the palm oil industry.

To achieve sub-objective (b), the scope of research includes:

(d) Configuring the capacity, raw materials input, and target production of the integrated processes using computerized process simulation.

(e) Developing a mass balance of the integrated process to verify the accuracy of the process simulation.

To achieve sub-objective (c), the scope of research includes:

(f) Configuring and comparing the economic performance of current technologies of the separate processes and the integrated processing complex based on CAPEX and OPEX.

(g) Applying the sustainability indices to assess and measure the sustainability performance of the integrated processing complex and its impact on the environment.

1.5 Research Contributions

The key contributions of this work are summarized as follows:

(a) A compilation of technical data for an existing process plant in the palm oil industry

A comprehensive technical data from the existing process plant is collected and compiled into a traceable database, including the milling, refining, and oleochemical processes based on on-site data collection and literature review.

(b) A process simulation of the existing process

The existing standalone process plant is simulated using Aspen Plus software based on the compiled technical data. The simulated process will be available as the basis for the integrated and scale-up estimation of any capacity.

(c) *A new conceptual integrated palm oil processing plant (upstream, midstream, and downstream)*

The newly proposed integrated palm oil processing plant is developed and introduced for consideration towards commercialization. The benefits and advantages of the integrated plant are presented in terms of economic and sustainability benefits. The verification of experts from industries and academics is presented in terms of design feasibility and technical capability of the integrated plant towards realization and commercialization and can be used as a basis for improvement in future research.

1.6 Thesis Outline

This thesis consists of 8 chapters. Chapter 1 gives an overview of the palm oil industry, problem background, problem statement, research objectives, and scope of research to develop the conceptual integrated palm oil processing (upstream, midstream, and downstream).

In Chapter 2, a literature review on the overview of the palm oil industry, existing palm oil processes (upstream to downstream), integration application in the process industry, process design and development, and process integration are discussed in detail. In addition, methods available for economic evaluation, sustainability assessment, and design verification are also being discussed to be selected for the validation and verification of the proposed integrated processing plant validation and verification.

Chapter 3 describes the overall research methodology, which involves the process development and design, process simulation, process integration, analysis on the design's feasibility, and the validation on the integrated design.

Chapter 4 discusses the results and discussion of the thesis. Section 4.1 discussed the process development and design, starting from the development of individual process to the development of integrated plant based on the integration of the individual process. Section 4.2 discussed the process simulation using Aspen Plus software including the simulation input and process simulation of the standalone processes and the integrated plant. This section also entails the verification and validation of the process simulation. Section 4.3 discusses the feasibility of the proposed integrated palm oil processing plant based on the economic evaluation and sustainability analysis. The economic evaluation is based on CAPEX, OPEX, and ROI. Sustainability performance is presented in terms of sustainability index scores of the carefully selected palm oil industry-related key performance index from Palm Oil Sustainability Assessment (POSA), Indonesia Bioenergy Sustainability Indicators (IBSI), and Palm Oil Mill Sustainability Index (POMSI). Section 4.4 discusses the results from the interview of the subject matter experts. Issues regarding the design and operation of the integrated plant are being discussed, and appropriate recommendations are proposed to improve the design feasibility and operational performance.

Finally, in Chapter 5, the study is summarized and concluded. Afterwards, several recommendations are included for future works to further convince on the commercialization of an integrated palm oil processing plant that covers the upstream, midstream, and downstream production in the palm oil industry.

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