DATA-DRIVEN MODELLING AND OPTIMIZATION OF PALM OIL REFINING PROCESS

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ABSTRACT

Bleaching earth and citric acid are expensive chemicals utilized in the palm oil refining process. Both chemicals are important in removing impurities such as colour pigments and other breakdown products in crude palm oil. The purpose of this study was to successfully develop refined oil quality prediction model and to optimize the dosage of bleaching earth and citric acid utilized in a palm oil refining process. First, response surface methodology (RSM) was used to develop an empirical model to relate the removal rate of free fatty acid (FFA) and red colour pigments in the refined oil to the dosage of both bleaching earth and citric acid. Next, artificial neural networks (ANNs) models were developed based on the pilot-scale experimental data and actual palm oil refining plant data as input and output data for the models. The quality parameters of crude oil (FFA and colour pigment content) as well as process parameters (bleaching earth and citric acid dosage, pressure and temperature of the deodorizer) were the input data while the quality of refined oil (FFA and red colour pigments content) were the output data. For comparison purpose, three types of ANN models were developed, which were multi-layer perceptron (MLP), stacked neural network (SNN) models and radial basis function neural network (RBFNN) models. All the ANN models developed were able to predict the quality of the refined palm oil. The developed models were compared and the best model, the SNN model, was chosen as the model for refined palm oil quality prediction. Finally, optimization frameworks to optimize the palm oil refining process were developed based on the multi-objective genetic algorithms approach using RSM and ANN models. The RSM models were validated by comparing the predicted value with the actual pilot-scale data, while all ANN models were validated by a new set of actual palm oil refining plant data. From the findings, bleaching earth dosage was found to be the major contributor to the impurities removal rate affecting the palm oil refining performance. Optimizing the dosage of bleaching earth and citric acid enabled significant savings in raw material usage, thus creating a more sustainable and cost-effective palm oil refining process. The models developed from this study were able to predict the quality of the refined oil accurately and quickly, gave the optimum dosage of the bleaching earth and citric acid, as well as provided optimum point of pressure and temperature of the deodorization process.

ABSTRAK

Tanah peluntur dan asid sitrik adalah bahan kimia mahal yang digunakan dalam proses penapisan minyak sawit. Kedua-dua bahan kimia ini penting dalam menyingkirkan bendasing seperti pigmen warna dan produk terpisah lain dalam minyak sawit mentah. Tujuan kajian ini adalah untuk membangunkan model bagi meramalkan kualiti minyak bertapis dan mengoptimumkan dos tanah peluntur dan asid sitrik yang digunakan dalam proses penapisan minyak sawit. Pertama, kaedah gerakbalas permukaan (RSM) digunakan untuk membangunkan model empirikal untuk mengaitkan kadar penyingkiran asid lemak bebas (FFA) dan kandungan pigmen warna merah dalam minyak bertapis dengan dos kedua-dua tanah peluntur dan asid sitrik. Seterusnya, model rangkaian saraf tiruan (ANN) dibangunkan berdasarkan data skala perintis dan data dari kilang pemprosesan minyak sawit sebenar sebagai data masuk dan data keluar model tersebut. Kualiti minyak mentah (FFA dan kandungan pigmen warna) serta parameter proses (dos tanah peluntur dan asid sitrik, tekanan dan suhu penyahbau) adalah data masuk sementara kualiti minyak bertapis (FFA dan kandungan pigmen merah) adalah data keluar. Untuk tujuan perbandingan, tiga jenis model ANN dibangunkan, yang terdiri daripada model *perceptron* pelbagai lapisan (MLP), model rangkaian neural bertindan (SNN) dan model rangkaian neural fungsi berdasar radial (RBFNN). Semua model ANN yang dibangunkan dapat meramalkan kualiti minyak sawit bertapis. Model–model yang dibangunkan dibandingkan, dan model terbaik, model SNN dipilih sebagai model bagi meramalkan kualiti minyak sawit bertapis. Akhirnya, kerangka pengoptimuman untuk mengoptimumkan proses penapisan minyak sawit dibangunkan berdasarkan pendekatan algoritma genetik pelbagai objektif menggunakan model RSM dan ANN. Model RSM disahkan dengan membandingkan nilai yang diramalkan dengan data sebenar skala perintis manakala semua model ANN disahkan menggunakan kumpulan data baharu dari kilang penapisan minyak sawit sebenar. Dari dapatan kajian, didapati dos tanah peluntur menjadi penyumbang utama kadar penyingkiran bendasing yang mempengaruhi prestasi proses penapisan minyak sawit. Mengoptimumkan dos tanah peluntur dan asid sitrik dapat mewujudkan penjimatan besar dalam penggunaan bahan mentah dan menghasilkan proses penapisan minyak sawit mentah yang lestari dan menjimatkan kos. Model yang dibangunkan dari kajian ini dapat meramalkan kualiti minyak sawit bertapis dengan tepat dan pantas, dapat memberikan dos optimum tanah peluntur dan asid sitrik, serta memberikan titik optimum bagi tekanan dan suhu proses penyahbauan.

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
AOCS	-	American Oil Chemists' Society
AV	-	Acid Value
BDPKOL	-	Bleached and Degummed Palm Kernel Olein
BE	-	Bleaching Earth
BP	-	Back Propagation
CA	-	Citric Acid
CCD	-	Central Composite Design
CCRD	-	Central Composite Rotatable Design
CIQ	-	China's Inspection and Quarantine Bureau
CPO	-	Crude Palm Oil
CPKO	-	Crude Palm Kernel Oil
CPKOL	-	Crude Palm Kernel Olein
CPKST	-	Crude Palm Kernel Stearin
DOE	-	Design of Experiment
FFA	-	Free Fatty Acids
GA	-	Genetic Algorithms
IV	-	Iodine Value
KOH	-	Potassium Hydroxide
MCPD	-	Mono-chloropropane-diol
MD	-	Molecular Distillation
MEOMA	-	Malayan Edible Oil Manufacturers' Association
MISO	-	Multiple Input Single Output

MIMO	-	Multiple Inputs Multiple Outputs
MLP	-	Multi-layer Perceptron
MSE	-	Mean Square Error
MOGA	-	Multi-Objective Genetic Algorithms
MOO	-	Multi-Objective Optimization
MPOB	-	Malaysian Palm Oil Board
NADES	-	Natural Deep Eutectic Solvent
NSGA-II	-	Non-dominated Sorting Algorithm II
O/S	-	Oil Surfactant
OSI	-	Oil Stability Index
paV	-	p-anisidine
PE	-	Processing Element
PCR	-	Principal Component Regression
PKOL	-	Palm Kernel Olein
PKST	-	Palm Kernel Stearin
PO	-	Palm Oil
PORAM	-	Palm Oil Refiners Association of Malaysia
PORIM	-	Palm Oil Research Institute of Malaysia
PV	-	Peroxide Value
R	-	Correlation Coefficient
RBDPO	-	Refined Bleached and Deodorized Palm Oil
RBF	-	Radial Basis Function
RBFNN	-	Radial Basis Function Neural Network
RMSE	-	RMSE Root Mean Square Error
RPO	-	Refined Palm Oil
RPKO	-	Refined Palm Kernel Oil
RS	-	Response Surface

RSM	-	Response Surface Metholody
SBE	-	Spent Bleaching Earth
SFE	-	Supercritical Fluid Extraction
SNN	-	Stacked Neural Network
USDA	-	United States Department of Agriculture

LIST OF SYMBOLS

R^2	-	Regression
R	-	Correlation coefficients
β_n	-	Regression coefficients
Y_i	-	Response variable
X_n	-	Independent variable
newff	-	Feed forward network
tansig	-	Tangent sigmoid transfer function
logsig	-	Log-sigmoid transfer function
purelin	-	Linear transfer function
trainlm	-	Levenberg-Marquardt learning algorithms
radbas	-	Radial basis transfer function
$Error_i$	-	Error of network without one variable
W	-	Quotient W of sensitivity analysis
W_n	-	Weights of neural network
b_n	-	Biases of neural network
x_i	-	Value of variable-x
y_i	-	Value of variable-y
$\bar{x}$	-	Mean of variable-x
$\bar{y}$	-	Mean of variable-y
N_{pop}	-	N population
N_{elite}	-	N elite population
Deo-P	-	Deodorizer pressure
Deo-T	-	Deodorizer temperature
w/w	-	Weight / weight (percentage)

RY	-	Red:Yellow colour ratio
gm	-	Gram
mL	-	millilitre
M	-	Molar
s	-	Second
e	-	Exponential
p	-	Probability value
3-D	-	Three-dimensional
2-D	-	Two-dimensional

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Elaeis guineensis, famously known as palm oil, is vegetable oil from the oil palm tree's fruit. The oils extracted from palm oil fresh fruit bunch may exist in two types; Palm Oil (PO) and Palm Kernel Oil (PKO). With a total yield of ~4 tons of PO and PKO per hectare per year, palm oil is the most productive oil crop globally, which is ten times more productive than soybean oils (*Malaysian Palm Oil Council, 2020)*. From 1980, palm oil has become the world's second most crucial vegetable oil after soybean oil (Sambanthamurthi,2000). The National Commodities Policy (NCP) 2011-2020 was formulated by Malaysian government to guide the Malaysian palm oil industry. A recent United States Department of Agriculture (USDA) report proved that palm oil is currently the world's main vegetable oil that counts 39 % of the total vegetable oils. Malaysia is the world's second-largest producer of palm oil (*United States Department of Agriculture (USDA)*, 2020). Palm oil is not only used as frying oil but also commonly used in the food processing industry to produce margarine, spreads, bread, cookies, cakes, filling creams, ice-creams, and non-dairy whipping creams and chocolate. Palm oil is widely used in frying fast food and manufacturing food products such as crisps, instant noodles, and infant formula. Other than the food industry, palm oil is also widely used in numerous other daily products such as soaps, cosmetics, and biofuel. Being the world's most versatile raw materials result in a rise in worldwide demand for palm oil since the 1980s.

This chapter gives a summary of palm oil production worldwide. Next, the research background and a problem statement will be described. This study's research objectives and scope relevant to the process modelling and optimization of the palm oil refining process are explained afterwards. Lastly, this chapter emphasizes this work's contributions regarding refined palm oil's quality prediction and process optimization**.**

1.2 Research Background

Crude Palm Oil (CPO) contains complex mixtures of majorly triacylglycerols (TAGs), and minorly monoacylgylcerol and diacylglycerol. These type of TAGs is depend on the components of the fatty acid in the TAGs. Fatty acids in oil palm generally contain 50 % saturated fatty acids, 40% monounsaturated fatty acids, and 10% polyunsaturated fatty acids. Each palm oil (palm oil, palm olein and palm stearin) can be differentiated using their palmitic acid proportions in the fatty acids. Other minor components in palm oil include Free Fatty Acids (FFAs), carotene, tocopherols, tocotrienols, phytosterols, moisture and impurities, sterols, phospholipids, glycolipids, and terpenic and paraffinic hydrocarbons (Goh et al., 1985; Tan and Nehdi, 2012).

FFAs can be increased by enzymes and microbial lipase in the palm fruit, resulting in a high level of FFAs in CPO. During storage, the oil reaction with water will produce FFAs, increasing the crude oil's FFAs content (Che Man et al., 1999). Consequently, the high level of FFAs (exceeding 5% of the standard requirement of FFA in CPO) makes it unhealthy for human consumption (Japir et al., 2017). Moreover, high carotene content in CPO results in a deep orange-red colour of the oil, while most consumers favoured light-coloured oil. Also, the high level of carotene in palm oil affects its oxidative stability (Tan and Nehdi, 2012). Besides, improper bleaching and degumming process will result in a poor quality of refined palm oil's colour, which is called colour reversion (Gibon, 2012). In short, these two undesired components of palm oil need to be lowered to a specific level by the refining process. Palm oil can be refined through a chemical or physical refining process (Ceriani and Meirelles, 2006; Gibon et al., 2007). Physical refining is more favoured than chemical refining because it is more suitable for producing edible oil and more environmentally friendly than chemical refining (Yang et al., 2008).

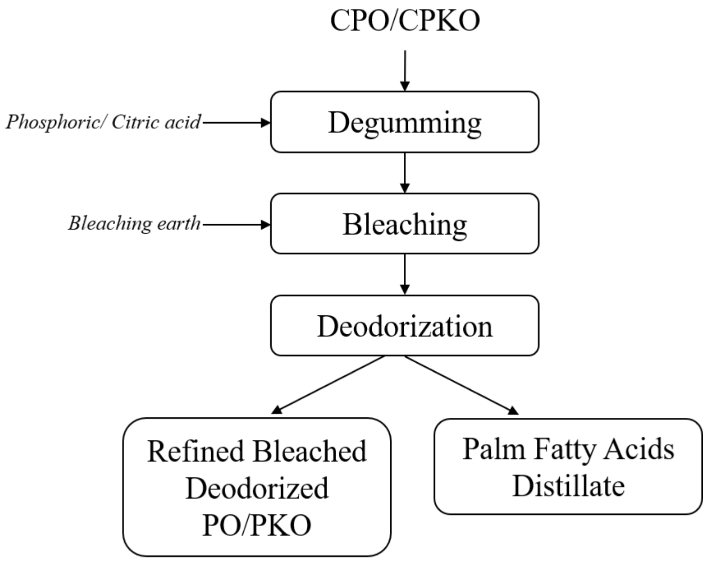

Figure 1.1 The palm oil physical refining process

Figure 1.1 illustrates the overall palm oil physical refining process. The degumming process involved the treatment of crude oil with a dilute acid such as phosphoric or citric acid, while the bleaching is a decolourization process in which the degummed oil is treated with special adsorbents (bleaching earth). Combining both processes improved the quality of the degummed and bleached oil. (Čmolík and Pokorný, 2000). Deodorization is the final palm oil refining process where the FFA, odour, flavour, and some colour pigment, and any other volatile minor undesired particles are removed from the CPO or CPKO by vacuum stripped method operated at high temperature (220°C-260°C).

The product quality in the palm oil refinery plant process is very crucial and essential to be taken care of. According to current practice in palm oil refinery plant, FFA content, colour, Iodine Value (IV), and moisture content are the major quality parameters. The specifications need to be accurately followed, or else the refined palm oil will be classified as an off-specification product. China, as the second-largest palm oil importer, had tightened the requirement on the quality of imported Refined Palm Oil (RPO). This results in theslow down on palm oil's demand and dropping the crude palm oil price.(*TheStar*, 2014). The new "landed quality" which are the new quality standard of the imported palm oil that has been introduced by China's Inspection and Quarantine Bureau's (CIQ) will make the off-specification RPO be rejected and not allowed to be re-refined in China (Adnan, 2013). Malaysian Palm Oil Board (MPOB) said that about 5% of the exported palm oil did not fulfil the new CIQ specifications in 2013, representing approximately 175 000 tons of palm oil. The palm oil refinery plant in Malaysia needs to control their RPO quality to avoid the risk of rejection. Thus, there is a need for improvement in the current operation of the palm oil refining industry.

1.3 Problem Statement

The fourth industrial revolution (IR 4.0) is the new growing trend towards automation and digitalization of industry. IR 4.0 includes the cyber-physical system, the Industrial Internet of Things (IIoT), and cognitive computing based on Artificial Intelligence (AI). Unfortunately, the palm oil industry has been moving slowly in this revolution. Currently, there is no automatic sensor for quality prediction in the palm oil refining process. The plant operator manually collects the refined oil sample, and its quality is manually check in the laboratory, which is time-consuming.

Also, in the current palm oil refining industry, the raw material dosage of bleaching earth and the citric dosage depends on the plant's operators' decision. From the observation made in the refinery plant and interview with the plant's expert, the main qualities focused by the palm oil refinery plant is the FFA content and colour of the refined oil. These qualities are checked several times throughout the refining process, especially after the combined degumming and bleaching process. The oil will be on-hold while the plant's operator sent the oil sample to the chemical laboratory. The oil will be sent out to the filtration process only after the quality of the FFA and colour is confirmed. If the quality does not meet the minimum specification, extra dosage of the bleaching earth and citric acid will be added to the process. This will increase the operating cost, and thus, a quality prediction model will be a good solution to this situation.

In line with IR 4.0, adopting digitalization tools in the palm oil refining industry for better decision-making will increase productivity and reduce operating costs. Therefore, there is a need to model the refined palm oil quality and optimize the palm oil refining industry's process parameters. The palm oil refining process's modelling is very difficult due to palm oil's complex chemical components. The quality of the crude palm oil varies as the chemical components vary. This complexity of chemical components in palm oil makes the first principal modelling of the palm oil refining process a difficult task to be accomplished. Thus, black-box modelling is a better choice in modelling of palm oil refining process.

Few literatures related to the modelling and optimization of the palm oil refinery plant process has been found. The application of RSM in palm oil refining was explored by Zulkurnain et al. (2013) in a specific modified refining process and by Ceriani et al. (2010) in a specific thin-film deodorizer simulation.The D-Optimal design in RSM application for palm oil refining has not been explored. The D-Optimal design is a straight optimization of number of run of an experiment where the optimality criterion and the model will be fixed. Besides, the application of the ANN in the palm oil refining process is focused on the specific Molecular Distillation (MD) process (Tehlah, 2016) and in predicting dosage of phosphoric acid and bleaching earth in experimental combined degumming and bleaching process (Morad et al., 2010). There is no application of ANN that utilize the real plant data found so far. Also, no literature on the hybrid method of RSM with Multi-Objective Genetic Algorithms (MOGA) and hybrid method of ANN with MOGA in the palm oil refinery industry was found. The MOGA method is an ideal method in solving multi-objective problems where it can find multiple optimal solution in one single simulation run. Therefore, the application of MOGA method in palm oil refining proces should be explored.

1.4 Objective of the Research

This research aims to develop a palm oil refining model integrating refined palm oil quality prediction and process parameter optimization. The objective is fulfilled through the Response Surface Methodology (RSM), Artificial Neural Network (ANN), and Multi-Objective Genetic Algorithms (MOGA) method. The details of the objective are as follows:

1. To develop empirical model of the combined degumming and bleaching process using Response Surface methodology (RSM) method.
2. To develop a quality prediction model of refined palm oil using experimental data and actual plant data utilizing the ANN model that represent the actual palm oil refinery plant process.
3. To optimise the palm oil refining process by minimizing the usage of raw material and maximizing the final quality of the palm oil refinery product.

1.5 Scope of the Study

The scope of the research is divided to two parts: pilot-scale plant and actual refinery plant. For pilot-scale plant,

i. The process is focused only on the combined degumming and bleaching process, without deodorization process. This is due to the limitation in accessibility of equipment by the plant.
ii. The research is limited only at the pilot-scale plant of the specific palm oil plant.
iii. The research focused only on two types of palm oil which are Crude Palm Kernel Olein (CPKOL) and Crude Palm Kernel Stearin (CPKST).
iv. The data from this pilot-scale plant experiment were used in developing correlation equations between process variables and removal rate of the impurities in the oil by utilizing RSM.
v. The developed correlation equations were then employed in optimizing the process variables.

For palm oil actual plant,

i. The process involved overall refining process which are the combined degumming and bleaching and the deodorization process.
ii. The data consist of variety types of oil such as CPKST, CPKOL, Crude Palm Oil (CPO), Crude Palm Kernel Oil (CPKO) and others. This is according to the type of oil run in a specific production date of the palm oil refinery plant.
iii. The overall process is based on the specific palm oil refinery plant only.

iv. The data from the actual refinery plant were used to model quality estimation model utilizing ANN.

The correlation by RSM using pilot-scale data and the ANN model utilizing the actual plant data have been programmed into MATLAB R2015b environment.

1.6 Research Contributions

This study fills the research gap in process modelling and optimization of palm oil refining. The existing research in palm oil modelling used simulation data obtained from simulation programs that do not fully represent the actual palm oil refining process in an actual refinery plant. Besides, the types of ANN that best represents the palm oil refining process have not been explored. The contributions of the thesis are enlightened below:

1. Quality estimation model based regression correlation based on RSM for utilizing pilot-scale plant data and an ANN model based on actual palm oil refining plant data were developed and shown to be viable for implementation in a real palm oil refining plant as a quality prediction sensor.
2. Optimization of the refined palm oil quality that minimizes the raw material usage while keeping the quality within the desired range by utilizing the hybrid RSM-MOGA and hybrid ANN-MOGA approach.
3. The optimum value obtained from this research can serve as a starting point in real palm oil refining plant optimization.
4. The methods used in this study which are hybrid RSM-MOGA and ANN-MOGA can serve as guideline in optimization of palm oil refining plant.

1.7 Thesis Outline

This thesis consists of five chapters and organized as follows:

Chapter 1 introduces the background of the study, problem statement, objective, research scope and significance of the research.

Chapter 2 covers the literature review and research gaps in the modelling and optimization of palm oil refining. The previous research on the process modelling of palm oil refining, RSM and ANN modelling in palm oil refining and palm oil refining optimization are reviewed.

Chapter 3 explains the detailed methodology of this research to fulfill the presented objectives. This chapter includes the data collection method in experimental work and actual refinery plant, development of process modelling of palm oil refining using RSM and ANN, and finally, the development of the optimization of palm oil refining process.

Chapter 4 describes the results from the RSM correlation, ANN modelling, and the hybrid RSM-MOGA and ANN-MOGA optimization frameworks and thoroughly discusses the fulfilled objectives.

Chapter 5 integrates the conclusions gained from the research done and some recommendations for future studies.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Sulaiman, N. S.**, Mohd-Yusof, K. and Mohd-Saion, A. (2018). Quality Prediction Modeling of Palm Oil Refining Plant in Malaysia Using Artificial Neural Network Models. *International Journal of Engineering & Technology*, *7*(3.26), 19-22. **(2016 -2019, Q4, IF:0.11)**

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1. **Sulaiman, N. S.** and Yusof, K. M. (2015). Artificial neural network-based model for quality estimation of refined palm oil. In *2015 15th International Conference on Control, Automation and Systems (ICCAS)* (pp. 1324-1328). IEEE. **(Indexed by SCOPUS)**