UNIVERSITI PUTRA MALAYSIA

PROCESS SIMULATION, EXERGY ANALYSIS AND OPTIMISATION OF PALM OIL MILLING PROCESS USING ASPEN PLUS

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By

UMMI KALSUM HASANAH MOHD NADZIM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Chair : Prof. Robiah Binti Yunus, PhD
Institute : Advanced Technology

One of the main concerns in Malaysian palm oil industry is the energy consumption issue which may jeopardize the sustainability of palm oil milling process as an energy-intensive process. Apart from reducing the oil loss during processing, it is crucial to determine whether the energy of the process is utilised efficiently and sustainably. The production of crude palm oil (CPO) involves a complex process influenced by the processing variables and environmental factors. To evaluate the relationship of oil loss and processing variables and also energy aspects of the CPO production, it is important to assess the performance of various unit operations in the palm oil milling process. Therefore, application of simulation tool is seen as an alternative and sustainable approach to resolve the abovementioned issues. Thus, this study performed a steady state process simulation of palm oil milling process using ASPEN Plus V8.6. By considering assumptions and limitations of the process, modelling and simulation of palm oil milling process was successfully conducted. The simulation model of palm oil milling process was validated with the results obtained from experimental analyses based on the component composition in several streams, namely oil, water (moisture), glucan and xylan contents through absolute error. It was found that most of components have error values below 5%. All the outlet streams from the simulation model were also compared with the estimated process mass balance retrieved from the palm oil mill and defined by absolute relative deviation. It was found that most streams have deviation values below 10% and between 10-15%. This indicated that the actual results were in good agreement with model prediction, although some unit operations indicated limitation during validation. Subsequently, exergy analysis of each unit operation of palm oil milling process was also conducted, where the physical exergy was obtained from the ASPEN Plus, and the chemical exergy and exergy of mixing were determined from the calculations. The exergy analysis revealed that steriliser has the highest exergy destroyed (69%) among other unit operations, signifying opportunity to improve the energy use of milling process. Thus, process optimisation was conducted using Central Composite Design (CCD) of response surface methodology (RSM) coupled with ASPEN Plus to investigate the effect of varying pressure (3-7 bar), sterilisation time (20–120 minutes) and steam mass flow (20–45% of FFB) on carbohydrate degradation and exergy destroyed of the sterilisation process. Results showed that glucan and xylan degradations producing glucose and xylose, respectively, were the highest at 5 bar pressure, 17550 kg/hr steam mass flow and 70 min sterilisation time with minimum exergy destroyed of 3493.9 MJ/hr. Under these conditions, the energy loss was reduced by 33.6% compared to that of conventional sterilisation conditions (5259.3 MJ/hr) at 3 bar pressure, 14500 kg/hr steam mass flow and 90 min sterilisation time. It can be inferred that the application of simulation tool such as ASPEN Plus is able to assist in predicting the performance and the use of energy of complex and energy-intensive process sustainably. The energy consumption of palm oil milling process could be effectively reduced using more appropriate operating conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PROSES SIMULASI, ANALISIS EKSERGI DAN PENGOPTIMUMAN PROSES PENGILANGAN MINYAK SAWIT MENGGUNAKAN ASPEN PLUS

Oleh

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Salah satu kebimbangan utama dalam industri minyak sawit Malaysia adalah isu penggunaan tenaga yang mungkin menjejaskan proses pengilangan minyak sawit sebagai proses yang intensif tenaga. Selain daripada mengurangkan kerugian minyak semasa pemprosesan, adalah penting untuk menentukan sama ada tenaga proses tersebut digunakan secara cekap dan mampan. Penghasilan minyak sawit mentah (CPO) melibatkan proses kompleks yang dipengaruhi oleh pembolehubah pemprosesan dan faktor persekitaran. Untuk menilai hubungan kehilangan minyak dan pembolehubah pemprosesan serta aspek tenaga pengeluaran CPO, adalah penting untuk menilai prestasi pelbagai unit individu dalam proses pengilangan minyak sawit. Oleh itu, aplikasi alat simulasi dilihat sebagai satu alternatif dan pendekatan yang mampan untuk menyelesaikan isu-isu yang disebut di atas. Oleh itu, kajian ini menjalankan proses simulasi keadaan mantap bagi proses pengilangan minyak sawit menggunakan ASPEN Plus V8.6. Dengan mengambil kira andaian dan limitasi proses, pemodelan dan simulasi proses pengilangan minyak sawit telah berjaya dilakukan. Model simulasi bagi proses pengilangan minyak sawit disahkan dengan hasil yang diperolehi daripada analisis eksperimen berdasarkan komposisi komponen dalam beberapa aliran, iaitu kandungan minyak, air (kelembapan), glukan dan xilan melalui ralat mutlak. Didapati bahawa kebanyakan komponen mempunyai nilai ralat di bawah 5%. Semua aliran keluar daripada model simulasi juga dibandingkan dengan anggaran keseimbangan jisim proses yang diperolehi daripada kilang minyak sawit dan ditentukan oleh sisihan relatif mutlak. Didapati bahawa kebanyakan aliran mempunyai nilai sisihan di bawah 10% dan antara 10-15%. Ini menunjukkan bahawa hasil sebenar adalah dalam perjanjian yang baik dengan prediksi model, walaupun sebahagian unit operasi menunjukkan limitasi semasa pengesahan. Seterusnya, analisis eksergi bagi setiap unit operasi proses pengilangan minyak sawit juga dijalankan, di mana eksergi fisikal diperolehi daripada ASPEN Plus, dan eksergi kimia dan campuran eksergi ditentukan daripada pengiraan. Analisis eksergi mendedahkan bahawa pensteril mempunyai eksergi termusnah yang tertinggi

(69%) antara unit operasi yang lain, menandakan peluang untuk menambahbaik pengunaan tenaga proses pengilangan. Oleh itu, proses pengoptimuman dijalankan menggunakan rekabentuk komposit sentral (CCD) daripada metodologi permukaan respon (RSM) yang digabungkan dengan ASPEN Plus untuk menyiasat kesan menvariasikan tekanan (3-7 bar), masa pensterilan (20-120 minit) dan aliran jisim stim (20-45% daripada buah tandan segar) terhadap degradasi karbohidrat dan eksergi termusnah bagi proses pensterilan. Hasil menunjukkan bahawa degradasi glukan dan xilan yang masing-masing menghasilkan glukos and xilos adalah tertinggi pada tekanan 5 bar, aliran jisim stim 17550 kg/hr dan masa pensterilan 70 minit dengan eksergi termusnah yang minimum iaitu 3493.9 MJ/jam. Di bawah keadaan ini, kehilangan tenaga dikurangkan sebanyak 33.6% berbanding keadaan pensterilan konvensional (5259.3 MJ/jam) pada tekanan 3 bar, aliran jisim stim 14500 kg/jam dan masa pensterilan 90 minit. Dapat disimpulkan bahawa penggunaan alat simulasi seperti ASPEN Plus dapat membantu memprediksi prestasi dan penggunaan tenaga bagi proses yang kompleks dan intensif tenaga dengan cara yang mampan. Penggunaan tenaga bagi proses pengilangan minyak sawit dapat dikurangkan secara efektif menggunakan kondisi operasi yang lebih sesuai.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variances
ARD	Absolute Relative Deviation
CCD	Central Composite Design
CPO	Crude Palm Oil
DGFORM	Standard Free Energy of Formation (25^{o}c)
DHFORM	Standard Enthalpy of Formation (25^{o}C)
EFB	Empty Fruit Bunch
EU	European Union
FFA	Free Fatty Acids
FFB	Fresh Fruit Bunches
LLE	Liquid-liquid Equilibrium
MPOB	Malaysia Palm Oil Board
MSPO	Malaysian Sustainable Palm Oil
NOS	Non-oily Solids
NRTL	Non-random Two Liquid
OER	Oil Extraction Rate
PCES	Property Constant Estimation System
POME	Palm Oil Mill Effluent
RCSTR	Continuous Stirred Tank Reactor
REF	Reference Environment
RSM	Response Surface Methodology
SEP	Separator Block
STEAM-TA	Steam Table
USB	Unstripped Bunches
VLE	Vapour-liquid Equilibrium

LIST OF NOTATIONS

$\dot{E}x_{tot}$	Total exergy of a stream
Ex_{chem}	Total chemical exergy of a stream
Ex_{phys}	Total physical exergy of a stream
$\Delta_{mix}Ex$	Exergy change of mixing
$Ex^{o}_{chem,i}$	Standard chemical exergy of any species *i*
$\Delta_f G^o_i$	Gibbs energy of formation of species *i*
$Ex^{o}_{chem,j}$	Standard chemical exergy of the element *j* in species *i*
η_j	Number of atoms of elements *j* in species *i*
$Ex^{o\alpha}_{chem,i}$	Standard chemical exergy of any species *i* in phase *α*
$Ex^{o\beta}_{chem,i}$	Standard chemical exergy of any species *i* in phase *β*
$\Delta_{\beta\rightarrow\alpha} G^o_i$	Gibbs energy of formation of species *I* changes of different phase
T_o	Reference temperature
P_o	Reference pressure
H	Enthalpy at
H_o	Enthalpy at reference condition $[T_o, P_o]$
S	Entropy at
S_o	Entropy at reference condition $[T_o, P_o]$
$\Delta_{mix}H$	Enthalpy of mixture at T and P
$\Delta_{mix}S$	Entropy of mixture at T and P

CHAPTER 1

INTRODUCTION

1.1 Sustainable palm oil

In 1917, oil palm was first cultivated in Malaysia (Jalani *et al.,* 2002; Basiron, 2007). Although its initial growth was very slow, the cultivation of oil palm has expanded and accelerated through large-scale investments for the past 50 years (Basiron, 2007). Overall economy of Malaysian is largely contributed by the export of palm oil industry which provides employment and income from exports (Malaysian Palm Oil Council, 2013). Export of palm oil accounts for 90% of total production, whereas the remaining 10% is for local use (Lee, 2011). In early 2018, the palm oil industry in Malaysia was shaken by the European Union (EU) proclamation to restrict the use and export of palm oil to the European countries by 2020. The restriction stems from sustainability issues which have recently emerged as main global concern. Consequently, exports and palm oil prices have extremely diminished and are of concern to the palm oil industry players. Sustainability and sustainable development have become the key components in addressing and managing technological changes which precede human development, without jeopardizing the environment (Widok and Wohlgemuth, 2011).

The rapid palm oil production is in line with the escalating demand and economic advantages to the country. This has prompted the palm oil industry players to seriously embrace sustainability in their decision-making. To refute negative claims against palm oil, sustainable palm oil should be resolved through sustainable development by enhancing palm oil production methods, incorporating efficient technological innovations, enhancing solid environmental and social policy measures, and expanding stakeholder engagement. Furthermore, the Malaysian Sustainable Palm Oil (MSPO) (Figure 1.1) established by the Malaysian government with the involvement of palm oil industry players is seen as an initiative to support this industry.

The main goal of the MSPO is to manage sustainability issues and challenges associated with various parties involved in the industry in complying with national laws and international agreements. These standards explain the need for sustainable production in the supply chain, ranging from raw materials to transportation to consumers. Smallholders are stimulated by the MSPO to establish, sustain and improve their operational practices within the framework of the management system towards attaining a sustainable palm oil production (The British Standards Institution, 2018). In June 2018, continuous urging from the palm oil producing countries and high demand from world's population has suspended the restriction. This suspension should be considered as an opportunity to earnestly boost efforts in realizing a sustainable palm oil industry.

As the second largest palm oil producer in the world, this could be an indication to the EU that Malaysia is not underestimating this issue.

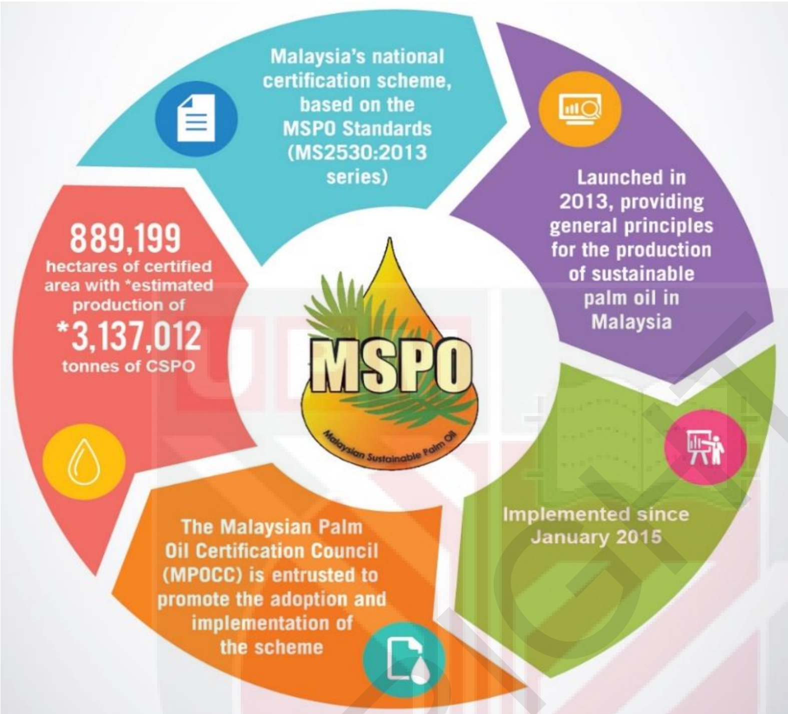

Figure 1.1: Malaysian sustainable palm oil (Adapted from Malaysian Palm Oil Council, 2013)

1.2 Problem statement

The issue of sustainability of palm oil production is not only associated with environmental impacts but also energy consumption (Andarani *et al.,* 2017) particularly in palm oil mills. At present, mills are paying more attention to milling operations, contemplating around FFB processing and oil extraction rate (OER). Little attention has been given to envisage palm oil milling process as an energy-efficient operation. The extraction process of vegetable oil is an energy-intensive process (Kong *et al.,* 2018), which includes palm oil milling process as the FFB sterilisation process consumes the highest amount of steam (Aziz *et al.,* 2015). Sterilisation process is the heart of the palm oil mill with significant roles to ensure the best quality and quantity of CPO production. Among its main functions are to deactivate enzyme responsible for quality deterioration (free fatty acid formation), loosen fruits in bunch for maximum recovery during threshing operation, soften fruit mesocarp and minimise kernel breakage from nut conditioning (Olie and Tjeng, 1982; Whiting, 1990; Hamzah, 2008; Aziz *et al.,* 2015). Furthermore, the quantity of CPO produced is highly dependent on the number of fruits stripped or separated from the bunch after sterilisation. This is referred to as carbohydrate degradation or hydrolysis, which is a chemical reaction, occurring only during the sterilisation process. This reaction plays a pivotal role in ensuring that the conditions of the sterilisation process employed favour this reaction to occur efficiently as demonstrated by the ability of fruit to detach or strip from the bunches.

In current practice, the FFB sterilisation process is carried out at a temperature of 131^{o}C and a pressure of 40-45 psi for horizontal steriliser, while continuous steriliser uses steam temperature of 100^{o}C at atmospheric pressure. Both conditions are sufficient to prevent the deterioration of oil quality due to the inactive lipase enzyme at 55^{o}C (Matthaus, 2012). However, sterilisation of FFB at 100^{o}C has been reported to induce low stripping efficiency (Noerhidajat *et al.,* 2016), which may generate unstripped bunches (USB) as well as decrease OER. There are also reports on the presence of USB from a few palm oil mills that use commercial horizontal sterilisers (Leong, 1990; Adzmi *et al.,* 2012). Vincent *et al.* (2014) concluded in their study that pre-processing conditions and sterilisation and extraction methods are the two factors that affect the oil yield and quality. If the existing operating conditions of the sterilisation process require modification through a series of experimental works, this will be expensive, time consuming and will consume high energy. Therefore, there should be an approach that is suitable in predicting the process characteristics and their reliance on design and operating variables sustainably.

On the other hand, numerous efforts have been made to improve the palm oil milling process by incorporating new technologies and modifying the operating conditions of a certain process which have been implemented in several palm oil mills. Nevertheless, process improvement in palm oil mill requires a lot of trial and error and could lead to process downtime. The occurrence of downtime in the manufacturing system may lead to throughput loss (Enginarlar *et al.,* 2002). According to Mohamad *et al.* (2011), downtime also creates disturbance to the entire production process, either scheduled by the management or unplanned shutdown due to machine malfunction. To reduce or eliminate such problems, simulation tool may assist mill managers to identify bottleneck and possible action to be taken in a faster way. Generally, simulation can be employed to exhibit possible effects of alternative conditions and actions (Sokolowski and Banks, 2009). It is an appropriate tool which can be used for predicting experiments with uncertain results.

In palm oil mills, simulation is rarely implemented for CPO production process as reported by a few researchers (Mohd-Lair *et al.,* 2012a; 2012b), as most of the existing simulation software programs are not particularly designed for CPO, unlike petroleum. Diaz-Tobar *et al.* (2010) contended that the complex nature of the lipid system has limited the penetration of process modelling into this industry. Computational simulation has been extensively applied for design, analysis and optimisation in the chemical and petrochemical industry but not vegetable oil industry. Currently, there are no commercial simulators that contain significant families of lipid compounds for vegetable oil industry in their database.

In fact, there is lack of studies on simulation and prediction of palm oil milling process improvement using simulator such as ASPEN Plus. In general, the simulation model is a representative of a conceptual model to the real process to facilitate process improvement without high expenses as well as save time and energy. This approach can also be employed to predict process improvement without having to go through the actual implementation (Lestari *et al.,* 2013) particularly for complex processes. Another advantage of simulation is its ability to substitute experimental works in real systems, either existing or still in the design phase (Law, 2006).

Nevertheless, this could lead to another challenge which is the limitation in estimating the accuracy of the simulation model and its results compared to the actual process. Any simulation model requires some assumptions and data input that will determine the outcome of the simulation. Although a good model has been developed using a process simulator, alternative setups and operating conditions will experiment on the computer (Petrides *et al.,* 2002). The process of constructing a model is susceptible to error as the real system is converted into a conceptual model (Harrel *et al.,* 2004). Thus, the model should be well validated to minimise the error. According to Law (2006), validation determines whether the simulation model represents the real system accurately. A validated model will assist decision-making, and the degree of difficulty to validate the model depends on the complexity of the process.

The capability of simulator such as ASPEN Plus in modelling complex production processes has been widely reported in various fields. Among them are gas-to-liquid process (Hao *et al.,* 2008), biomass gasification in fluidized bed reactor (Nikoo and Mahinpey, 2008), biodiesel and bioethanol (Gutierrez *et al.,* 2009; Silva *et al.,* 2013; Yun *et al.,* 2013), batch fermentation (Carvajal *et al.,* 2010), palm oil waste combustion (Ismail *et al.,* 2012) and biojet fuel production process (Gutierrez-Antonio *et al.,* 2013). In addition, the software enables the extensive use of available databases for chemicals and physical parameters allowing for built-in operation units which are suitable for sensitivity analysis and modelling of various processes. Despite the application of ASPEN Plus in other fields, this approach has not yet been employed in palm oil milling process.

To bridge the gap, ASPEN Plus is used to model and simulate palm oil milling process particularly for CPO production to improve its efficiency in energy use. Subsequently, validation of simulation model and results is conducted using results obtained from the experimental analysis and palm oil mill. Energy consumption for existing and modified operation conditions of sterilisation process is determined through exergy analysis based on exergy efficiency and exergy destroyed. Since sustainability can be associated with energy consumption as abovementioned, the efficiency of energy usage should be justified if some process modifications are performed to the existing palm oil milling process. This can assist in evaluating if the energy is being utilised sustainably and efficiently. Thus, exergy efficiency concept is crucial as it measures how closely the actual performance of the production process closes to ideality (Duván Martinez *et al.,* 2016). Moreover, exergy analysis also points out causes and locations of energy degradation in a process, prompting process and technology improvements (Tan *et al.,* 2010). Sensitivity analysis and process optimisation are also performed in this study, emphasizing on carbohydrate degradation and exergy destroyed of steriliser employing ASPEN Plus combined with response surface methodology (RSM) to obtain the best operating condition with minimum energy loss to the environment.

1.3 Research objectives

This study has several main objectives as follows:

1. To conduct steady state simulation of palm oil milling process employing ASPEN Plus.
2. To compare and validate the simulation results with data obtained from the mill and a few experimental analyses.
3. To evaluate the exergy efficiency and exergy destroyed of each equipment in the palm oil milling process.
4. To optimise the carbohydrate degradation and exergy destroyed of steriliser using ASPEN Plus combined with response surface methodology (RSM).

1.4 Scope and limitation of study

The scope of this study is to model and simulate the palm oil milling process focusing on CPO production using ASPEN Plus. Since certain equipment in the existing process deals with high energy consumption, modifications are necessary to sustain CPO production. Nevertheless, modification activities for process improvement involve significant costs and could disrupt the actual process. Therefore, simulation method is required prior to actual implementation. The art of this research is to model and simplify the complex palm oil milling process involving various materials and equipment into ASPEN Plus software, which allows the use of mostly simpler model equipment and a limited database for the components involved. To ensure the reliability of the simulation model, the results obtained are validated with experimental analysis and estimated mass balance of the process. Subsequently, this study applies a combination of ASPEN Plus and response surface methodology (RSM) to optimise the exergy destroyed and carbohydrate degradation of sterilisation process at various operating conditions.

On the other hand, it is essential to highlight that this study is limited only to CPO production process, excluding palm kernel oil production to reduce complexity in constructing the simulation model. The main limitation of this study is the unavailability of actual data from palm oil mill for validation purposes, particularly the mass balance of the palm oil milling process. Moreover, this process has various complex components and unit operations which could complicate the simulation convergence. Some chemical components related to palm oil are not available in the existing ASPEN Plus databank which requires several assumptions and built-in component to enable the execution of process simulation.

1.5 Thesis outline

This thesis comprises five chapters.

Chapter 1 starts with introduction focusing on sustainable palm oil issue. This chapter also highlights problem statement, objectives, and scope and limitation of this study.

Chapter 2 covers the brief description on conventional palm oil milling process, literature reviews on the application of simulation in vegetable oil industry and ASPEN Plus simulation software. This chapter also highlights the exergy analysis including the optimisation of energy-intensive process using ASPEN Plus combined with response surface methodology (RSM) of various fields.

Chapter 3 describes the methodology for process simulation, model validation, exergy analysis of the palm oil milling process and optimisation of carbohydrate degradation and exergy destroyed of sterilisation process using ASPEN Plus and RSM.

Chapter 4 presents the results and discussion based on research objectives. Finally, Chapter 5 summarises the conclusion and significant results of this study as well as includes recommendations for future work.

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LIST OF PUBLICATION

Journal publications

Ummi Kalsum Hasanah Mohd Nadzim, Robiah Yunus, Rozita Omar and Bo Yuan Lim (2020). Factors Contributing to Oil Losses in Crude Palm Oil Production Process in Malaysia: A Review. *International Journal of Biomass and Renewables, 9(1),* 10-24.

Ummi Kalsum Hasanah Mohd Nadzim, Robiah Yunus, Rozita Omar and Mohd Halim Shah Ismail (2021). Optimisation of energy consumption in sterilization process using ASPEN Plus and response surface methodology. *Journal of Oil Palm Research* (SUBMITTED).

Poster publications

1. Ummi Kalsum Hasanah Mohd Nadzim, Robiah Yunus and Rozita Omar (2016). Simulation of Sterilization Process using ASPEN Plus. Presented in Palm Oil Milling Technology Colloqium (POMTeC'16), 2016, UiTM Shah Alam, Malaysia.

2. Ummi Kalsum Hasanah Mohd Nadzim, Robiah Yunus, Rozita Omar and Mohd Halim Shah Ismail (2019). Simulation of Palm Oil Milling Process using ASPEN Plus. Institute of Advanced Technology (ITMA) Open Day, 5 December 2019, UPM.

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