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Economic and Performance Analysis of Bioethanol Production from Aren and Palm Biomass Using Ionic Liquid with SuperPro Designer as a Transportation Energy Transition Strategy

Ihsan Maulidin[1], Amaliyah Rohsari I. Utami[1*], Sri Sugiwati[2]

[1]*Department of Engineering Physics, Faculty of Electrical Engineering, Telkom University, Jl. Telecommunication. 1, Terusan Buahbatu - Bojongsoang, Telkom University, Sukapura, Kec. Dayeuhkolot, Bandung, Indonesia 40257*

[2] *Chemical Research Center, National Research and Innovation Agency, B.J. Habibie Building, Jl. M.H. Thamrin No. 8, Central Jakarta, Indonesia 10340*

Abstract

This Increasing energy consumption has caused energy availability to become increasingly scarce, especially in Indonesia. Therefore, developing renewable energy sources, such as biofuels, is becoming increasingly important to support the energy transition in the transportation sector. One type of biofuel that is promising is bioethanol, which can be produced from biomass such as sugar palm and palm oil. However, the development of bioethanol still faces obstacles in terms of effectiveness, time, and production costs. Performance and economic analysis of bioethanol production from sugar palm and oil palm biomass with ionic liquid (IL) has been carried out using SuperPro Designer (SPD) software. This process begins with testing biomass characteristics to determine the most optimal sugar palm composition. Simulations with experimental conditions show that the optimal IL and biomass ratios are 1 g/g, resulting in ethanol concentrations of 92 g/L and 94 g/L, respectively, close to the theoretical results with 96% conversion of biomass to ethanol. Ethanol production on a factory scale shows cost reductions of up to 30% from initial prices. With the abundant availability of biomass, bioethanol production from sugar palm and palm oil has great potential to be developed in Indonesia, supporting the energy transition strategy in the transportation sector and reducing dependence on fossil fuels.

Kata kunci: *bioethanol, biomass, ionic liquid, SuperPro Designer*

1. Introduction

Increased energy use globally, especially in the transportation sector, has resulted in greater reliance on fossil fuels. This has led to several problems, including declining energy reserves and increased greenhouse gas emissions. In Indonesia, the transportation sector contributes 37% to total national energy consumption, mainly from fossil fuels such as gasoline and diesel (Setyono & Kiono, 2021). This is also supported by an increase in fuel sales, which reached 80.4 million kiloliters in 2023. This dependence threatens national energy security and exacerbates environmental impacts due to growing carbon emissions. Energy transition measures towards cleaner and more sustainable energy sources are needed to meet this challenge. One promising alternative in this regard is biofuels, particularly bioethanol, which can be produced from various types of biomass (MEMR, 2023).

Bioethanol is one type of renewable fuel that can be produced from lignocellulosic biomass resources, including agricultural waste, wood, and non-food crops. In Indonesia, palm oil (Elaeis guineensis) and palm (Arenga pinnata) have great potential to be processed into bioethanol. As a major producer of palm oil in the world, Indonesia produces significant amounts of biomass waste, such as empty bunches, shells, and fibers. In addition, the sugar palm that thrives in Indonesia also produces sap, and other parts of the plant can be utilized for bioethanol production. This potential makes Indonesia a strategic country in developing bioethanol as an alternative energy source.

Bioethanol production from lignocellulosic biomass still faces several challenges from both technical and economic perspectives. One of the main challenges is the biomass pretreatment process, which requires a high cost and a long time. The complex structure of

*) Corresponding Author.
E-mail: amaliyahriu@telkomuniverisity.ac.id

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lignocellulosic biomass, especially lignin, which is challenging to break down, is an obstacle in the conversion process to ethanol (Webliana, Sukma Rini, Forestry, Mataram University Agriculture, & Education, n.d.). To overcome this problem, using ionic liquid (IL) as a solvent has proven effective in increasing pretreatment efficiency (Rohsari, Utami, Sulaeman, & Mel, 2020). ILs uniquely dissolve various lignocellulosic components in biomass, thereby improving enzyme accessibility to cellulose and hemicellulose during the conversion process to ethanol (Utami, Sulaeman, & Mei, 2021).

In addition, to estimate and optimize bioethanol production on an industrial scale, SuperPro Designer (SPD) simulation software was used. SPD is a simulation tool that enables economic and technical analysis of the biomass-derived bioethanol production process, including the pretreatment stage using ionic liquid, fermentation, and ethanol purification. A thorough production performance analysis can be conducted by utilizing SPD, which can help identify important aspects that can improve efficiency and reduce production costs (Rohsari et al., 2020).

Within the energy transition framework, the development of bioethanol derived from palm biomass and oil palm in Indonesia partially shows significant potential to replace fossil fuels in the transportation sector. In addition to reducing carbon emissions, this initiative can strengthen national energy security by utilizing abundant and renewable natural resources. Therefore, conducting an economic and performance analysis of bioethanol production from palm biomass using ionic liquid and SuperPro Designer as part of Indonesia's energy transition strategy is important.

2. Methods

2.1. Pretreatment using Ionic Liquid (IL)

Pretreatment in bioethanol production involves separating the lignin component of lignocellulosic biomass to obtain cellulose and hemicellulose components. There are three steps in simulating palm biomass into ethanol: pretreatment, enzymatic saccharification, and fermentation and distillation. In biorefineries, bioethanol production is currently focused on environmental issues and reducing carbon dioxide emissions. The most important process in bioethanol production is the pretreatment process, which breaks down the cell wall to facilitate the enzymatic process. The residual solvent in this process must be environmentally friendly and reusable. The most effective pretreatment for bioethanol production currently uses Ionic Liquid (IL). IL is an ionic compound or salt that can be used continuously and is environmentally friendly. IL also has low toxicity compared to compounds used in pretreatment, such as acids, bases, and other compounds, making it easier for enzymes to bind to substrates and work optimally in forming glucose and xylose (Ninomiya et al., 2017).

After the *pretreatment* process, the biomass will be hydrolyzed using enzyme catalysts in the enzymatic saccharification process. Enzymatic hydrolysis or saccharification is the stage of the process of breaking down polysaccharide compounds in lignocellulosic biomass into its constituent sugar monomers with the help of enzymes that work specifically. Some sugar hydrolyzing enzymes that play an important role in the bioconversion of lignocellulose into bioethanol include cellulase and hemicellulase enzymes. The enzymatic saccharification process will produce sugars with C6 groups, such as glucose, and sugars with C5 groups, such as cellulase, fructose, and arabinose. These sugars will later be used as the main ingredient or carbon source in the fermentation process with the help of microorganisms to obtain ethanol. Ethanol from fermentation will go through a purification or distillation process before being used as bioenergy (Mulyaningtyas & Sediawan, 2019).

2.2. Simulation Design Using Super

The simulation design uses SPD software to simulate various chemical processes in biorefineries. SPD software has a complete set of procedures or tools for the simulation design of bioethanol production. The first step in simulation design is registering the components used in bioethanol production. The components that must be

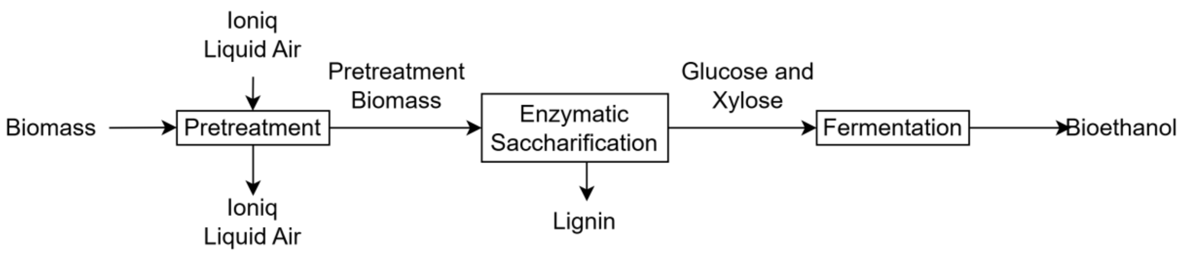

Figure 1. Block diagram of bioethanol fabrication system using the Ionic liquid method

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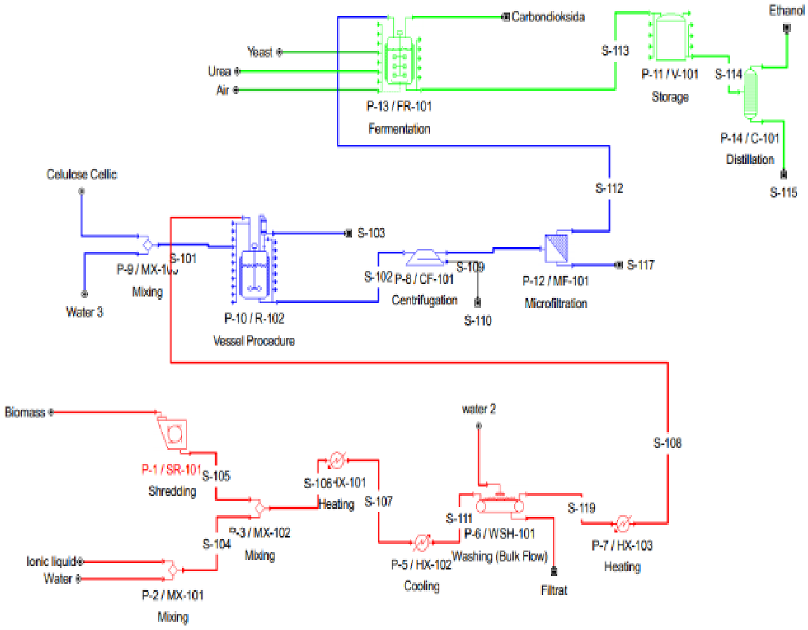


Figure 2. Overall bioethanol fabrication system using ionic liquid

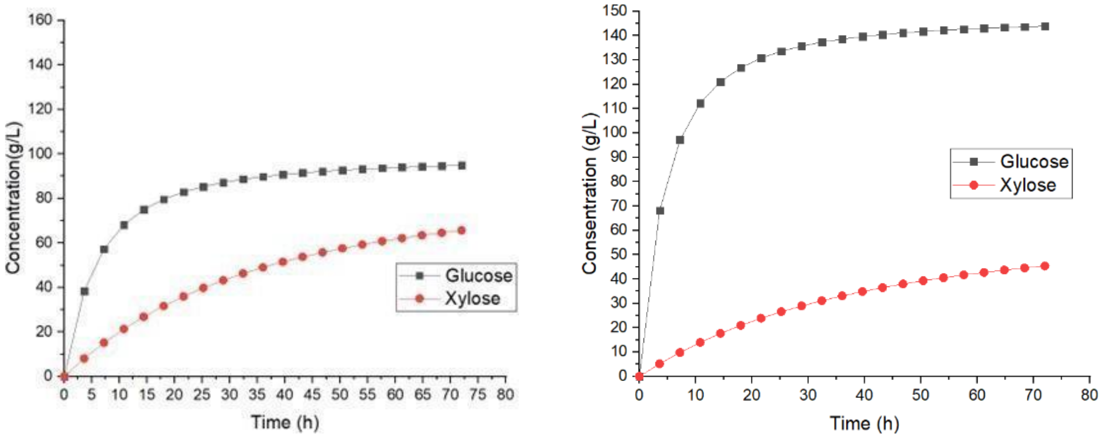
registered include raw materials and output compounds such as sugar and ethanol, which are directly involved in the reaction process in saccharification and fermentation. In addition, several conditions must be registered, such as molecular weight, molecular formula, and various physical and chemical conditions of the compounds used in bioethanol production.

After component registration, the equipment used in the bioethanol production process is selected. Each stage has a procedure unit that can simulate the work of the process. Each piece of equipment is set up with its unit of work, which is adjusted to the actual experimental conditions for bioethanol production. The configuration of each procedure unit and the mass and energy flows are then performed to observe and evaluate the entire system's performance. The production process must be carried out systematically with data even though the simulation and experimental results have been carried out previously.

2.3. System Operation

2.3.1. Main Architecture

The leading architecture of the bioethanol fabrication system using the IL pretreatment method is pretreatment, enzymatic saccharification, and



(a) (b)

Figure 3. Saccharification reaction rates of (a) palm and (b) palm oil

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fermentation. In the pretreatment architecture, several parts consist of shredding, mixing, heating, cooling, and washing. All parts of the pretreatment architecture are connected to get pretreatment results. Furthermore, the enzymatic saccharification architecture consists of test tubes equipped with enzyme input, centrifugation, and microfiltration equipment to filter sugar before fermentation (Faizall, Fitriani Ariko, Iw Yogamina, & Chemical Engineering, 2011; Singh, Simmons, & Vogel, 2009). Finally, the fermentation architecture consists of a fermenter tube equipped with yeast input used in the fermentation process. The output of the fermentation is bioethanol, which is used as fuel.

2.3.2. User Interaction

In this simulation method, the user can input biomass, which in this study is palm and sugar palm waste biomass, enzymes, and IL, with specific concentrations that can be adjusted in the simulation. In addition, there are also temperature and time settings for each unit of the process procedure that will be carried out in making bioethanol. Users can control the output of each process to minimize errors. The output control also facilitates the analysis of the bioethanol yield, such as economic analysis, concentration analysis, and the effectiveness of the fabrication design.

2.3.3. Algorithms and sub-system

In the pretreatment, the biomass of sugar palm and oil palm was converted into a smaller size and sieved using a chopper to a size of 250 - 500 um. Then, the biomass was mixed with IL and heated at 100ºC for 5 hours on a heating device. After that, the suspension was cooled to a temperature of 25º with a cooling device. Then, it was put into the washing device to separate the IL from the pretreated biomass; if so, the sample was dried with a heating device at a temperature of 90ºC. The pretreatment process ends when the treated biomass enters the reactor to proceed to the saccharification process.

Furthermore, the enzymatic saccharification stage is carried out in a vessel procedure reactor in which the mixing process between cellulose, hemicellulose, and lignin with cellulase and hemicellulase enzymes is operated at a constant temperature of 50ºC for 72 hours. Then, the sugar solution is put into a centrifuge for lignin precipitation. Then, the precipitation results are poured into a microfiltration device to filter out lignin and materials that are not needed in the fermentation process, especially those that are micro-sized. The last stage in this simulation is the fermentation stage; this stage is operated using a fermentation reactor, where the sugar solution will be given to yeast to produce ethanol (Mabrouki, Abbassi, Guedri, Omri, & Jeguirim, 2015). The ethanol produced will be stored and then distilled to obtain pure ethanol for fuel.

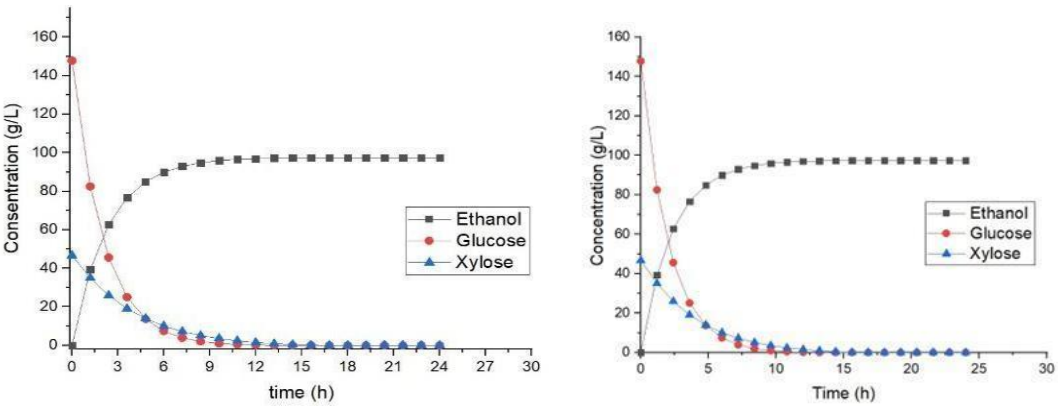
2.4. Economic Analysis

The economic analysis was conducted based on BEP (Break Event Point) calculations to obtain several economic analysis results, such as total expenses, income, and total operations in bioethanol production. In the simulation, to obtain optimal economic results, the input was conducted on a matrix ton scale with the condition that the ethanol produced is the main revenue component in the simulation system (Barrera, Amezcua-Allieri, Estupiñan, Martínez, & Aburto, 2016). In addition, the overall costs, such as raw materials, energy consumption, and facility costs used in designing the bioethanol production system, were analyzed. The results of the economic analysis will allow us to compare the simulated ethanol yield with the current ethanol yield in Indonesia.

3. Results and Discussion

3.1. Pretreatment Results

The pretreatment process resulted in component analysis with experimental experiments to determine the lignocellulosic components in the palm and oil palm biomass used. The component analysis process resulted



(a) (b)

Figure 4. Reaction time for ethanol formation (a) palm and (b) palm oil

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in the percent composition of cellulose, hemicellulose, and lignin from the total biomass of sugar palm and palm oil.

The component analysis showed that cellulose concentration was 28%, hemicellulose was 32%, and lignin was 40% for palm biomass. The cellulose concentration was 40.3%, hemicellulose was 18%, and lignin was 41.7% for oil palm biomass. These results show that the concentration of lignin is enormous in the component analysis that has been carried out.

This is because the parts of palm biomass used for component analysis are the trunk and empty bunches, which are both complex parts. This is due to the characteristics of lignin, a hard material that becomes the wall of cellulose and hemicellulose in lignocellulosic waste. However, with a cellulose and hemicellulose concentration of more than 50% and the availability of aren palm and oil palm in Indonesia, aren palm and oil palm have the potential to be used as raw materials in bioethanol production to support the energy transition.

3.2. Enzymatic Saccharification

The pretreatment process is the key to entering the enzymatic saccharification process to obtain the desired sugar that can be converted into ethanol. The component analysis results of pretreated palm and palm biomass make it easier to simulate in SuperPro Designer software. Enzymatic saccharification breaks down cellulose and hemicellulose polymers into C6 and C5 sugars. The process takes place with the help of cellulase and hemicellulase enzymes that form a substrate-enzyme complex. The reaction equation was determined and set up in the simulation with biomass as the reactants and glucose and xylose as the reaction products. The determination of sugar concentration produced and observed through the saccharification reaction rate graph is based on chemical stoichiometry in the saccharification reactor (Hwang & Ku, 2014; Webliana et al., n.d.). The enzymatic saccharification reaction rate is shown in **Figure 3**.

The reaction rate of saccharification shown in **Figure 3** shows that after scarification for 72 hours, it is by the experimental process. It can be analyzed that the rate of formation or hydrolysis of glucose from cellulose produces more sugar compared to the hydrolysis of xylose from hemicellulose. This is because the cellulose polymer has one monomer, glucose, with a carbon six functional group that is easily disconnected during hydrolysis. At the same time, hemicellulose is a complex sugar polymer that contains not only xylose but several other C5 sugar polymers, such as fructose and arabinose. So, it takes an enzyme that works specifically to hydrolyze all the C5 sugars in the hemicellulose polymer.

In addition, the enzymatic saccharification reaction rate data in **Figure 3** shows that at 20 hours, the graph is constant for glucose formation from cellulose. This could be a recommendation for bioethanol production, making bioethanol production more efficient by reducing the enzymatic saccharification time. This also applies to the saccharification of hemicellulose to xylose; although at 20 hours, the formation of xylose continues, the increase in xylose concentration is not very significant. Using SuperPro Designer software simulation can make recommending the most optimal reaction time easier. Glucose 92 g/L and xylose 40 g/L were obtained with a conversion percentage of palm biomass to sugar of 94%. As for the conversion of palm biomass, 138 g/L glucose and 32 g/L xylose were obtained with a conversion of biomass to sugar of 96%.

3.3. Fermentation

The results of cellulose and hemicellulose saccharification in glucose and xylose will go through the fermentation stage. Preparatory steps at this stage include supernatant settling and micro-scale filtration to remove disturbances and maximize fermentation results. Micro-scale filtration is done to facilitate microorganisms in the

Table 1. Summary of economic costs in SuperPro Designer software simulations with palm biomass

Economic Analysis	Rate
Total Capital Investment	218,512,000 $
Operating Cost	42,140,000 $/yr
Total Revenues	100,090,000 $/yr
Cost Basis Annual Rate	713,667 kg MP/yr
Unit Production Cost	59.05 $/kg MP
Unit Production Revenue	140.25 $/kg MP
Gross Margin	57.90 %
Return On Investment	15.91 %
Payback Time	6.28 years
IRR	12.58 %
NPV	98,838,000 $

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Table 2. Summary of economic costs in SuperPro Designer software simulations with Palm biomass

Economic Analysis	Rate
Total Capital Investment	233,936,000 $
Operating Cost	42,249,000 $/yr
Total Revenues	106,734,000 $/yr
Cost Basis Annual Rate	885,955 kg MP/yr
Unit Production Cost	47.69 $/kg MP
Unit Production Revenue	120.47 $/kg MP
Gross Margin	60.42 %
Return On Investment	16.54 %
Payback Time	6.05 years
IRR	13.20 %
NPV	119,567,000 $

form of yeast in converting sugar into ethanol. This is undoubtedly very important in improving the performance of the yeast used. Furthermore, the fermentation process occurs in a simulated fermenter by setting the rate and reaction equation with glucose as a reactant and ethanol and carbon dioxide gas as products and emissions. The fermentation reaction rate results obtained using the SuperPro Designer software simulation are shown in **Figure 4.**

Similar to the reaction rate of sugar formation from the enzymatic saccharification process, **Figure 4** shows the results of the fermentation reaction rate, where the reaction rate of glucose concentration decrease is faster than xylose. This is because the condition of the C5 cyclic carbon bond is more difficult to break than C6. Meanwhile, the fermentation reaction rate showed that the ethanol concentration produced was 92 g/L for arenes and 94 g/L for 13 hours, with an ethanol conversion presentation of 96%.

3.4. Economic Analysis

The economic analysis is based on simulation results with large-scale inputs ranging from 100 to 150 matrix tons (MT). After experimenting using simulation, at an input of 100 MT, the economic analysis obtained is stable with gross margins and NVP that provide benefits in production. These results are obtained assuming the software calculates the price of the facilities or instrumentation directly. However, because SuperPro Designer is a software that can simulate and calculate large-scale production well, the simulation results can be used as a reference in bioethanol production, especially with palm biomass. The economic summary obtained using the simulation can be seen in **Table 1** and **2.**

In **Tables 1** and **2, which** show the comparison between the two bioethanol production projects, palm oil shows advantages in several significant aspects. Despite its higher initial investment and operating costs compared to palm, palm oil's larger production capacity, higher gross margin (60.42% versus 57.90%), and better Return on Investment (ROI) (16.54% versus 15.91%) make palm oil bioethanol a more economical option for large-scale production. In addition, palm oil's shorter payback period (6.05 years versus 6.28 years) and higher Net Present Value (NPV) ($119,567,000 versus $98,838,000) further strengthen its position as a more profitable alternative in the long run.

Bioethanol produced from palm has several advantages. Despite its higher per-unit production cost ($59.05/kg compared to $47.69/kg), the per-unit revenue from bioethanol ($140.25/kg) exceeds that from palm oil ($120.47/kg). This makes palm a promising feedstock for small- to medium-scale projects, especially in areas more suitable for palm cultivation. In addition, bioethanol from palm can increase the diversification of biofuel sources, which is crucial for strengthening energy security.

Regarding the energy transition in the transportation sector, bioethanol derived from palm oil and sugar palm has a significant contribution to make. Both can potentially reduce dependence on fossil fuels, especially in biofuel-producing countries like Indonesia. Replacing or blending fossil fuels with bioethanol can substantially reduce greenhouse gas emissions and support local economies through increased bioethanol production.

4. Conclusion

In the context of energy transition in the transportation sector, bioethanol produced from palm oil shows advantages in terms of production scale, cost efficiency, and long-term potential to meet clean energy needs. In contrast, while having a higher per-unit revenue, palm-derived bioethanol can be a strong option for small-scale projects or in areas that are difficult for palm oil to reach. Both have a significant role in diversifying renewable energy sources and can contribute to global transport sector decarbonization efforts. Using bioethanol as a blended fuel or as the primary fuel for vehicles could

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be an important step in achieving green energy and sustainability targets.

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