A Cold-inflow Free Solar Chimney Dryer for Seaweed Drying in Sabah, Malaysia

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Abstract

In seaweed industry, the post-harvest handling process of seaweed is an essential stage before shipping. The quality of dried seaweed focuses particularly on its moisture content for obtaining better selling price in the trading market. In the traditional and conventional methods, low technologies and economic drying process (i.e. platform method, hanging method) is widely implemented in Malaysia. In recent years, passive dryer (solar chimney dryer or greenhouse dryer), active dryer (dehumidifier dryer) and hybrid dryer (wind turbine, double-pass solar collectors with fins and v-groove) were developed for post-harvest handling process. However, there are in early stages of development and it is required to model and optimize before technologies are transferred to industry for application. A solar chimney dryer that is cold-inflow free, economic fossil fuel free and no additional electrical devices through the enhancement of flow is proposed in seaweed industry and might be favoured by those farmers whom used to the conventional technology. Consequently, a natural convection solar dryer that incorporated with flow enhancing chimney and cold-inflow free was designed and tested in the Faculty of Engineering, Universiti Malaysia Sabah to understand drying behaviour of seaweed as well as thermal performance of the solar chimney dryer. The drying process was then modelled mathematically to describe the seaweed drying process. The results showed that Page model was the best model to describe the solar drying kinetics of seaweed in the solar chimney dryer. The Henderson and Pabis model may be the most effective model to describe the drying kinetics of seaweed since nearly all the models perform satisfactorily with determination of coefficient (R^2=0.91-0.98) in describing the solar drying kinetics in the solar chimney dryer.

Keywords
Seaweed, chimney, solar drying, solar dryer, modeling

1. Introduction

Carrageenan is a family of sulfated polysaccharides that extracted from red algae. It is useful addictive in food industry for gelling, thickening, emulsifying and preserving foods and drinks. Carrageenan tends to be in vegan products as it is plant based and used to replace gelatin which is extracted from animal. *Kappaphycus* and *Eucheuma* are red algae species that grows widely in Malaysia, Indonesia and Philippine. Sun drying is traditionally and conventionally postharvest handling process by spreading on a platform or by hanging with rope at coastal areas as shown in Figure 1. It is an essential process to dry fresh seaweed for shipping. However, open sun drying process requires larger area and prone to contamination during raining seasons due to re-moistening.

a) Platform Method b) Hanging Method

Figure 1. Traditional and conventional post-harvest handling process

Solar drying is an alternative drying process that has been proposed to avoid product quality loss instead of shade drying.Solar drying performance is highly dependent on the design and operation of solar dryers. Motorized and mechanically-driven fan dryers are mostly not feasible and affordable due to high capital and lack of energy supply at coastal area. Therefore an economic, green, easy to operate and maintain solar dryer might serve as an important tool for postharvest handling process to prevent losses. Dried seaweed with desired moisture content fetches better price in the trading market. It helps those farmers to improve their income with better quality of dried seaweed.

In recent years, there are types of solar dryer have been developed and tested for seaweed drying process such as passive dryer (Phang et al. 2015), active dryer (Djaeni & Sari, 2015) and hybrid dryer (Ali et al. 2014, Fudholi et al. 2013, Othman et al. 2012) were developed for post-harvest handling process. However, there are in early stages of development and it is required to model, optimize and scale up before technologies are transferred to industry for application. A solar chimney dryer which is short in drying time, cheap, environmental friendly, fossil fuel and favoured by farmers should be investigated for development purpose. In this study, a solar chimney dryer which is easy to operate and maintain as well as close to conventional drying process for seaweed drying was constructed and tested in the Faculty of Engineering, Universiti Malaysia Sabah.

2. Materials and Methods

2.1 Preparation of Sample

Fresh seaweed was obtained from Semporna, Sabah and packed using polystyrene box for 1 day for shipping from Tawau to Kota Kinabalu. A pretreatment method is encouraged in post-harvesting process for mini estate project in Semporna due to the limited space on the platform. The fresh seaweed was washed, packed into polyethylene bags (PE) and put on the cement floor in the open area for dehydration for one day. The dehydrated seaweed was then taken out from the PE bag and weighed before introduced into the solar drying system.

2.2 Solar Drying System

A prototype natural convection solar dryer with draft enhancing chimney was designed and constructed where a schematic diagram of the experimental set up is illustrated in Figure 2.

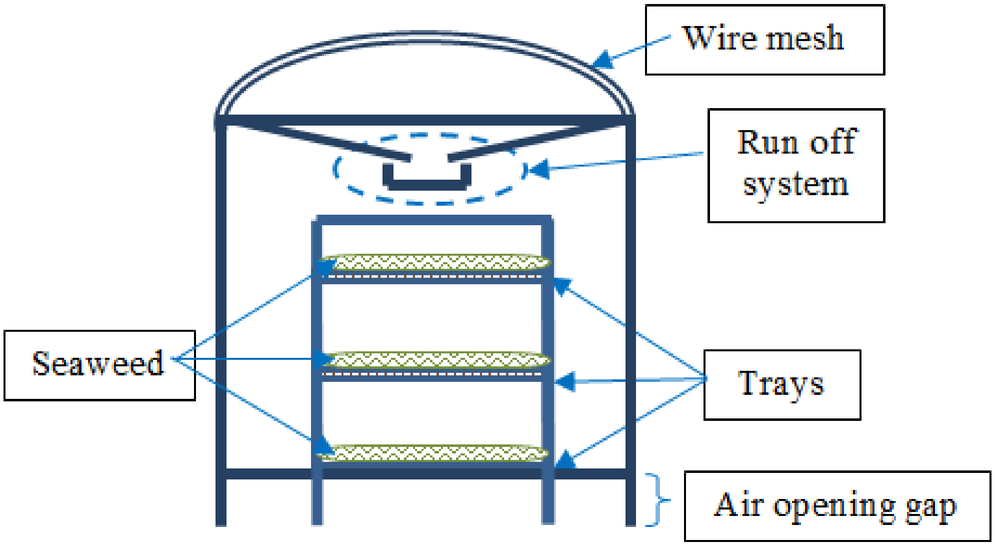

Figure 2: Schematic diagram of proposed solar chimney dryer prototype

The solar dryer consists of air opening at the bottom of dryer, drying chamber with trays and a draft enhancing chimney fitted with wire mesh at the top. The chimney with wire mesh is a novel design which prevented cold inflow and has as high as 90% improvement on air velocity in term of efficiency if compared to conventional chimney (Kumaresan, 2013). Thus, it is believed that the proposed solar chimney dryer that fitted with wire mesh has better draft enhancement if compared to conventional natural convection solar dryer.

2.3 Experimental Procedure

Studies on the prototype natural convection solar dryer (8′L×5′W×8′H) with draft enhancing chimney were conducted at the Faculty of Engineering at Universiti Malaysia Sabah. The air temperature and relative humidity inside the solar dryer and surrounding were recorded using data logger (Testo 174H, USA) with an interval of 10 minutes. The average initial moisture content of seaweed that was introduced into the solar dryer on each tray (2′×3′) was measured. A representative sample on each tray at top, middle and bottom was taken every 3 hours to weigh the weight of seaweed during the experiment duration. The experiment was terminated when the difference of seaweed weight less than 5% for the subsequent measurement. The representative sample of seaweed from each tray was then sent to oven for moisture content measurement using the AOAC method at 105°C for 24 hours.

2.4 Mathematical Modeling

The drying data was modeled to investigate the drying characteristic of seaweed in the proposed solar dryer. Thin layer drying models were used is listed in Table 1. These semi theoretical and empirical models that applied are derived from Fick's Second Law which were simplified and added with empirical coefficients to improve curve fitting. The empirical models show a relationship which is derived from moisture content and drying time has not taken account effect of physical properties.

Table 1. Thin layer drying models tested for solar seaweed drying.

Equation No.	Model	Equation
1	Lewis	$MR = \exp(-kt)$
2	Henderson and Pabis	$MR = a \exp(-kt)$
3	Page	$MR = \exp(-kt^n)$
4	Modified Page	$MR = \exp(-k(t)^n)$

The moisture ratio (MR) is defined as $(M_i-M_e)/(M_0-M_e)$ where the subscripts denote i at time i, e at equilibrium and 0 at the initial. Non-linear regression was implemented using the least square method. The determination coefficient (R^2) and root mean square error ($RMSE$) were used as statistical analysis for selecting the best model that described the proposed solar drying system for seaweed.

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \qquad (5)$$

where SSE is the sum of squared error, SSR is the sum of squared residuals and SST is the sum of squared total which explained the proportion of variance accounted for the dependent variable by the model.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp})^2\right]^{\frac{1}{2}} \qquad (6)$$

where $MR_{pre,i}$ is predicted moisture ratio and MR_{exp} is experimental moisture ratio.

3. Results and Discussion

The naturally ventilated solar chimney dryer is implementing greenhouse as well as chimney ventilation concepts. The solar drying system consisted of a drying chamber, a run off system, air opening gaps at the bottom, a rack of trays and an enhancing chimney that fitted with wire mesh at roof top. The heat entrapped in the drying chamber and the vapour was discharged through the chimney at roof top. In order to compare the drying time of seaweed drying under shade and in a naturally ventilated solar chimney dryer, the study has been reported by Phang et al. 2015. The total time that has been taken for seaweed drying was six days. One day was taken for pretreatment process in PE bags aims to reduce the water content where 54.06% of the water content was reduced before being introduced into the solar chimney dryer. Five days drying time was taken in the proposed solar chimney dryer for seaweed drying where the equilibrium moisture content (M_e) achieved. Figure 3 shows the average air temperature and relative humidity of the drying chamber as well as the air temperature and relative humidity of surroundings during seaweed drying.

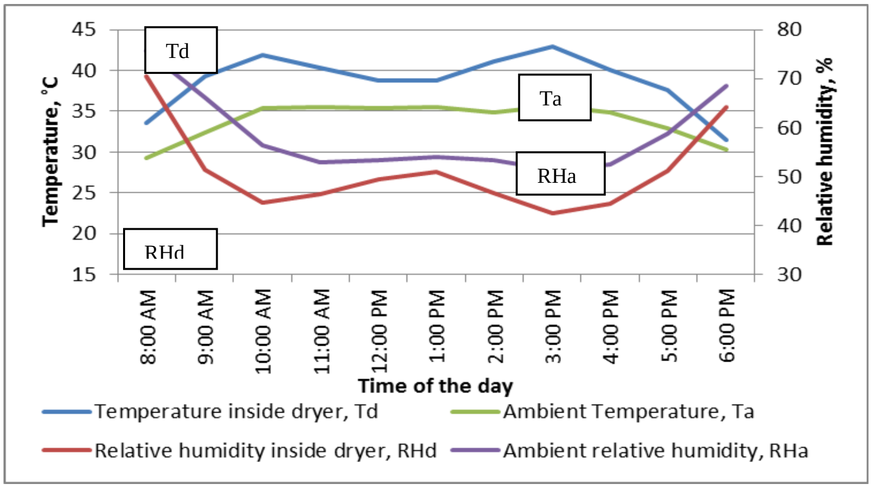

Figure 3: Air temperature and relative humidity for both surrounding and drying chamber at various time of the day during experiment

In the drying chamber, the air temperature was in the range of 31°C to 43°C whereas the air relative humidity was in the range of 42% to 71%. In the day time, the difference of air temperature between drying chamber and surrounding was as high as 7.34% whereas the difference of air relative humidity between drying chamber and surrounding was as high as 14.89%. The difference of average air temperature and average air relative humidity between drying chamber and surrounding hourly of the day for 5 days is shown in Figure 4. The drying process in solar chimney dryer only occurs during day time due to the solar irradiation effect but not in the night time when sunlight was not available. It is due to the air saturated in surrounding and flows into the solar dryer from the air opening at bottom when air temperature cooled down during night time. The average air temperature in drying chamber for 5 days was not as high as expected at 12.00pm; it might due to the cloudiness of sky.

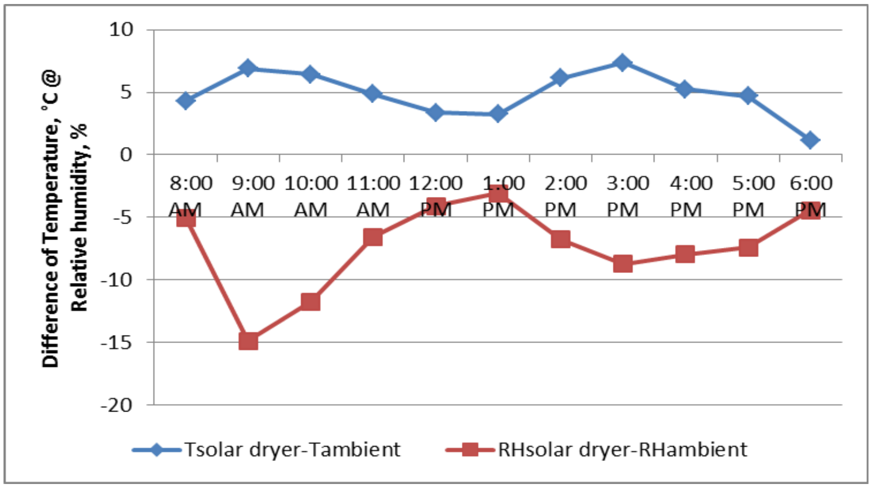

Figure 4: The difference of average air temperature and average relative humidity between drying chamber and surrounding hourly

The moisture content data was taken in the beginning from 8 am till 5 pm daily. The drying curve of seaweed, moisture ratio versus drying time for 120 hours, 5 days in the proposed solar dryer was showed in Figure 5. The average initial moisture content of seaweed for the top, middle and bottom tray was 81.88% (wb) when the sample was first introduced into drying chamber at 5pm. The drying characteristic of seaweed in the dryer showed that the drying process did not occur in the drying chamber in between 5 pm to 5 am when the sunlight was not available.

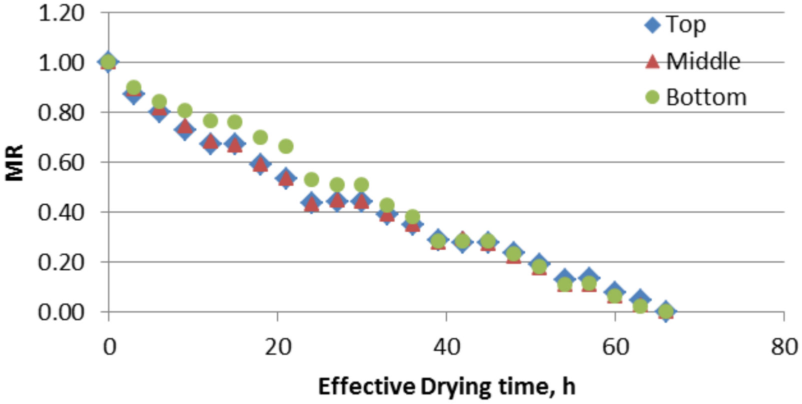

Figure 5: Moisture ratio of seaweed on tray at top, middle and bottom in the proposed dryer

The solar drying process ended after 120 hours which was equivalent to 5 days in total. The weight of the representative seaweed samples was found to be quite close to each other at different tray positions. The final moisture content of seaweed measured from top, middle and bottom were 29.61% (db), 51.83% (db) and 39.09% (db) respectively as illustrated in Figure 6.

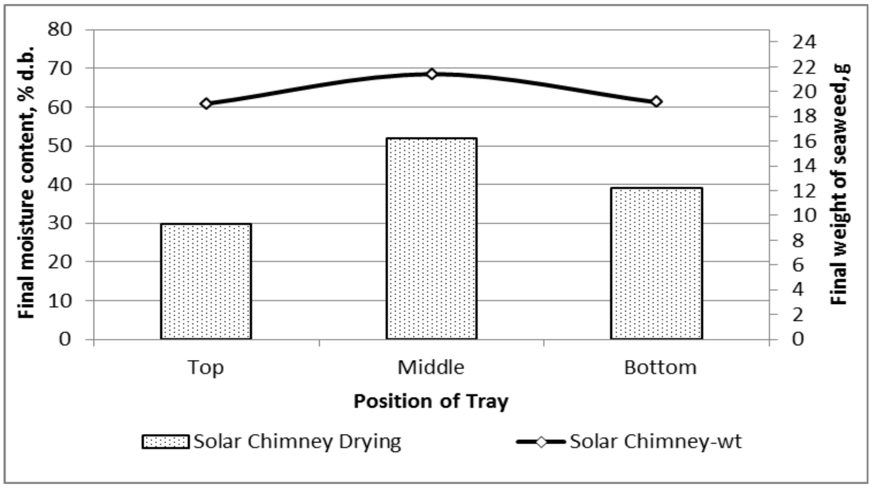

Figure 6. Final moisture content of seaweed on each tray in solid chimey dryer

Although the weight of the seaweed at the top, middle and bottom tray were almost the same in the drying curve, the total bound water in the seaweed was different. There is a 37% in difference for the top tray and middle tray whereas the difference for middle and bottom was less than 5%. The effect of solar irradiation on the top tray in the solar dryer is significant and vital. The final moisture content of seaweed was slightly higher at the middle tray if compared with the bottom tray. It may be due to the enhancement of draft that caused by the chimney effect (Kumaresan et al. 2013). In order to make sure the seaweed achieves the required moisture content (wb), the sample in the middle tray can be used a reference point to determine the final moisture content. The drying models for seaweed drying were fitted to the experimental data where the statistical analysis through curve fitting for drying models is presented in Table 2.

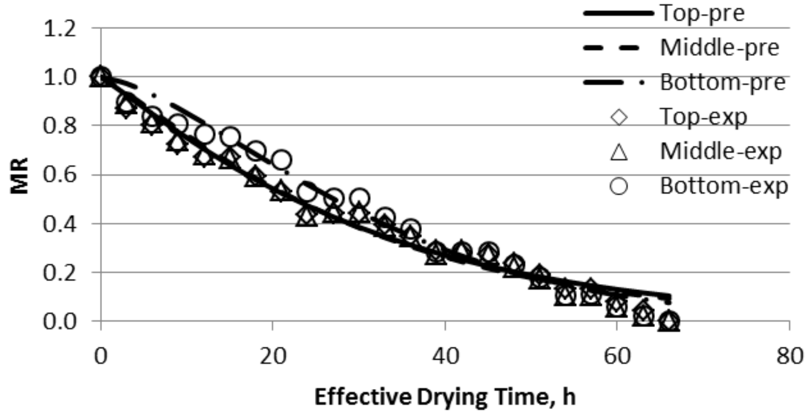

Figure 7: Moisture ratio of seaweed on tray at different position in the proposed dryer

The Page model was the best model to describe the drying behaviour of seaweed based on the highest value of determination coefficient and lowest value of *RMSE* for top, middle and bottom tray. The curve fitting of Page model to the experimental data at each tray is shown in Figure 7. A similar drying model was also chosen to describe the drying kinetics of seaweed in a convection solar dryer (Othman et al. 2012, Fudholi et al. 2011). The accuracy of model application for seaweed drying in both solar chimney dryer and forced convection solar dryer is as high as 96% by comparing experimental and predicted data.

Table 2. Non-linear regression analysis using curve fitting for solar seaweed drying

Tray position	**Model**	**Constants coefficients**	R^2	***RMSE***
Top	Lewis	k= 0.0321,	0.9707	0.0451
	Henderson &Pabis	a= 1.0014, k= 0.0322	0.9708	0.0451
	Page	n= 1.0928, k = 0.0232	0.9757	0.0428
	Modified Page	n= 0.0688, k= 0.4668	0.9707	0.0451
Middle	Lewis	k= 0.0325	0.9655	0.0492
	Henderson & Pabis	a=1.0188, k= 0.0332	0.9676	0.0487
	Page	n= 1.1476, k= 0.0194	0.9758	0.0439
	Modified Page	n= 0.0698, k= 0.4656	0.9655	0.0492
Bottom	Lewis	k= 0.0290	0.9173	0.0758
	Henderson & Pabis	a= 1.0706, k = 0.0313	0.9378	0.0711
	Page	n= 1.4706, k = 0.0054	0.9786	0.0451
	Modified Page	n= 0.0619, k = 0.4696	0.9173	0.0758

4. Conclusion

The Page model which is the best fitted model was selected based on the highest value of determination of coefficient (R^2) and lowest value for *RMSE* to describe drying kinetics of seaweed on top, middle and bottom tray in drying chamber of a solar dryer with draft enhancing chimney. The Henderson and Pabis model may be the most effective model to describe the drying kinetics since nearly all models perform satisfactorily value of determination coefficient (R^2=0.91-0.98) in describing the solar drying kinetics of seaweed in the solar dryer with a draft enhancing chimney.

In order to improve the drying rate of seaweed drying in the solar dryer, the design of solar dryer as well as construction materials shall be further developed and investigated so that scale up process become possible for seaweed industry

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Appendix A. Curve fitting for drying models

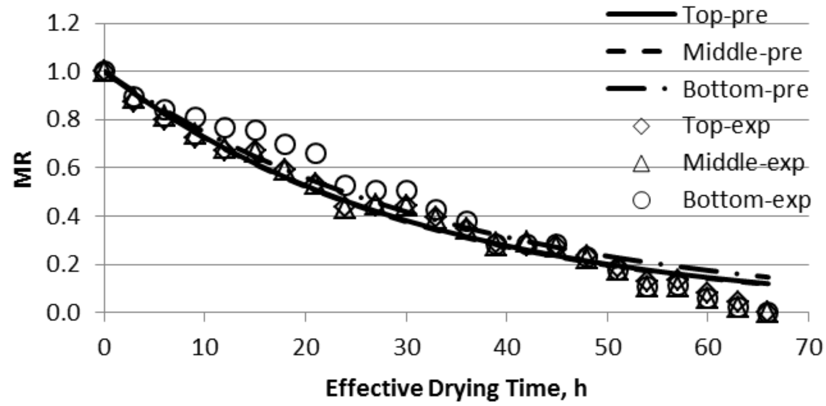

Figure A1: Curve fitting of Lewis model to experimental data

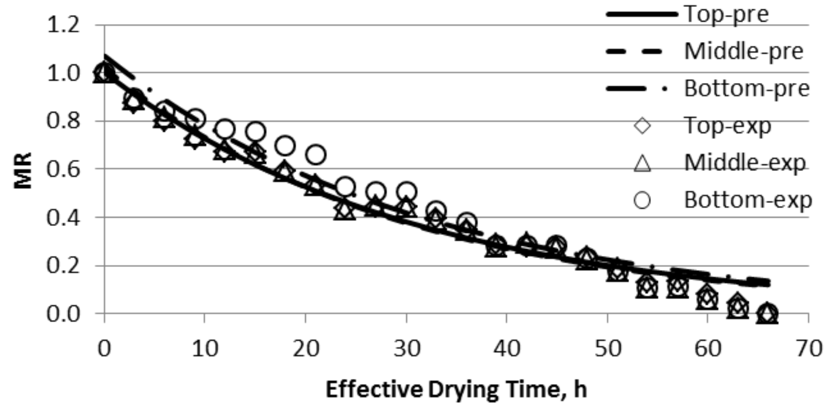

Figure A2: Curve fitting of Henderson and Pabis model to experimental data

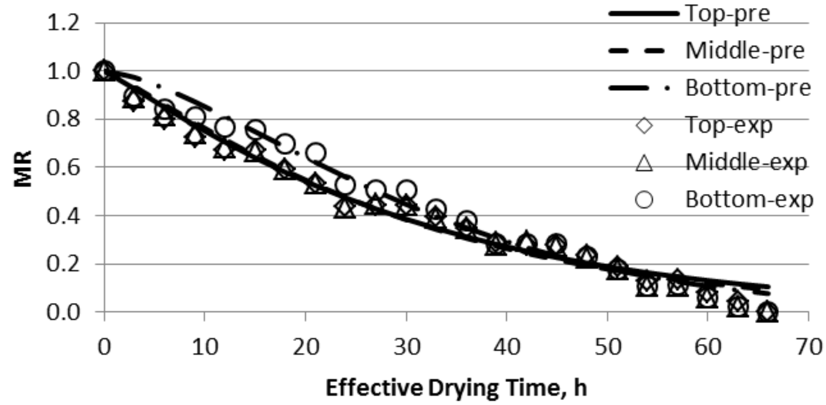

Figure A3: Curve fitting of Modified Page model to experimental data

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Biographies

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