Acta Sci. Pol. Technol. Aliment. 23(1) 2024, 5–14

www.food.actapol.net pISSN 1644-0730 eISSN 1898-9594 http://doi.org/10.17306/J.AFS.001149

ORIGINAL PAPER

Received: 9.07.2023
Accepted: 22.10.2023

MODEL KINETIC AND TECHNO-ANALYSIS OF MORINGA LEAVES HOT AIR-DRYING PROCESS FOR SUSTAINABILITY DEVELOPMENT

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ABSTRACT

Background. The economic worth of moringa leaves may increase if drying is applied to the leaves to produce a powder. This is a source that can be applied to a variety of food products instead of using it as animal feed or discarding it. In addition, the key factors that affect a product's quality and impact on the environment are its energy consumption and quality change.

Material and methods. In this study, the impact of various drying temperatures (55–70°C) on kinetic behaviour, effective moisture diffusivity coefficient (D_{eff}), activation energy (E_a), specific energy consumption (SEC), rehydration index, hunter whiteness, and gas emissions was evaluated.

Results. Seven models were applied and fitted on actual data for the drying process. Among these, Page showed the best fit, with high R^2, low RMSE (Root-mean-square error), and low Chi-square. The results showed that D_{eff} and E_a values were $8.36 \times 10^{-12} - 1.22 \times 10^{-11}$ m²/s and 20.14 kJ/mol, respectively. The energy consumption of drying the moringa leaves ranged from 39.92 to 154.01 kWh/kg. The high in hunter whiteness and low in gas emissions were found when the sample was dried at 65–70°C.

Conclusion. The grade of dried moringa leaves and the amount of energy used were both significantly influenced by temperature. Additionally, the first data concerning the amount of energy used to dry moringa leaves also offer greater details on the impact of drying on environmental carbon emissions. To ensure sustainable agricultural production in the future, research aiming at enhancing product quality and reducing environmental consequences should be carried out and put into practice.

Keywords: drying model, energy consumption, kinetic, moringa leaves, sustainable

INTRODUCTION

Moringa oleifera is the most common species of woody plant in the genus Moringa in the family *Moringaceae*. This plant is native to South Asia but also grows wild and is grown, exploited, and used in many places in tropical and subtropical countries due to its high economic value. In countries where this plant is found, *Moringa oleifera* is used as a vegetable and in processed foods because of its nutritional properties. The leaves are high in protein, rich in flavonoids, carotenoids, and ascorbic acid, and contain essential amino acids (Anwar

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et al., 2005; Stadtlander and Becker, 2017). The leaves of the *Moringa oleifera* plant also offer a variety of medicinal properties, including resistance to germs, fungi, and viruses. Other benefits of moringa leaves include antioxidant activity and cardiovascular system protection (Dhakad et al., 2019). However, following harvest, moringa leaves frequently have a high moisture content and are susceptible to microbiological, enzymatic, and chemical responses. The treatment and drying of moringa leaves are also an essential goal of the food business and ensure sustainable agriculture by making good use of the leaves for further processing procedures with high quality and sensory value.

Because it removes the water from fresh produce and prevents the impacts of procedures that harm fresh agricultural raw materials, drying is a preservation technique that is frequently employed in the food sector. Because it requires less equipment and has a wide range of applications, hot air drying is frequently utilized in industrial production (Zhou et al., 2019). Energy efficiency, heat transfer rate, and higher heat flow are factors that affect the drying rate and consequently, the effective reduction of drying time, water activity, protection of the color, and maintenance of the nutrients in the finished product (Huang et al., 2021; Orikasa et al., 2015; Tai et al., 2021). In addition, mathematical modeling is crucial for determining the ideal drying conditions to increase the shelf life of food ingredients while drying leafy crops. To produce dried goods of the highest quality, this activity is also used to design and enhance industrial drying systems (Thuy et al., 2021a; Thuy et al., 2022a; Thuy et al., 2022b).

Energy consumption has become a major issue in recent years, both in terms of industry spending and long-term global environmental challenges (Menon et al., 2020; Rehman et al., 2022). Because some countries have laws that punish excessive greenhouse gas (GHG) emissions, both circumstances are discussed, taking CO_2 emissions into consideration (Pérez-Won et al., 2023; Thuy et al., 2022a). However, there are negative effects that directly affect human health, such as the use of chemicals and fossil fuels (Koondhar et al., 2021). One of the biggest issues the world is currently facing is the energy problem. Therefore, it is crucial to investigate ways to lower emissions or look into reliable, secure, and durable energy sources (Motevali et al., 2014). The impacts of the global crisis have not been spared by the food business. The utilization of diverse energy sources throughout each step, from farm to plate, as well as technical processes, relates food production to its environmental impact both directly and indirectly. Furthermore, the usage of fossil fuels has caused global warming, which is now a major issue on a global scale. Most greenhouse gas emissions worldwide are caused by fossil fuels, which are utilized in power plants to generate electricity. The processing and drying sectors use the most energy in the agriculture business given its significance in terms of power consumption (Kaveh et al., 2020). Farm practices are linked to the formation and release of greenhouse gases. Because the drying process necessitates a huge quantity of energy, these emissions are particularly significant (Kaveh et al., 2020). The effect of drying conditions on drying behavior was evaluated. The drying process variables and gas emission potential were estimated to obtain good quality moringa powder with the lowest energy use. These results had far-reaching implications when applying moringa leaves drying technology on an industrial scale, creating high quality moringa powder products for the subsequent production processes of food products with the addition of powdered moringa leaves.

MATERIALS AND METHODS

Preparation moringa leaves

The green moringa leaves were collected and treated in a solution of $NaHCO_3$ concentration from 1% for 15 minutes to maintain the color of the leaves during the drying process (Rani et al., 2021). The air velocity was maintained at 0.5 m/s and and a fixed 30% relative humidity. The leaves were drained and dried in a hot air dryer (Model SIBATA SD-60, Japan) at different temperatures (55, 60, 65, and 70°C) until the moisture content remained about 6% wet basic. Three replicates were conducted. The moringa leaves were arranged in thin layers (about 1 cm thickness) on many pre-weighed trays (20 × 20 cm); each tray had about 500 grams of leaves. The weight of the tray and total weight (tray and leaves) were recorded. The calculation of moisture content calculated on both a wet and dry basis was based on the changing weight (considered as moisture loss) during the drying process (each 30 min). The moisture ratio (MR) was simplified and calculated as the ratio of initial moisture content on a dry basis, and the same moisture content was determined at each recorded time (kg water/kg dry matter) (Akpinar et al., 2003). Each experimental point represents the mean value of three replications.

Seven thin layer drying models, including Henderson and Pabis, Modified Henderson and Pabis, Logarithmic, Newton, Page, Two-term, and Wang and Singh (Akpinar et al., 2003), were fitted to the drying data to select the best model suitable for describing the drying process of moringa leaves (Table 1). The Stagraphics Centurion XV.I was used to determine the model constants. The best fit of model was based on the the root mean square error (RMSE), coefficient of determination (R^2), and chi square (χ^2).

Table 1. Seven thin layer drying models used in this study

Model name	Model equation
Henderson and Pabis	MR = a.exp(–kt)
Logarithmic	MR = a.exp(–kt) + c
Newton	MR = exp(–kt)
Page	MR = exp(–k(t^n))
Two-term	MR = a.exp(–kt) + b.exp(–k_ot)
Modified Henderson and Pabis	MR = a.exp(–kt) + b.exp(–gt) + c.exp(–ht)
Wang and Singh	MR = 1 + a.t + b.t^2

Drying behavior

The effective diffusivity (D_{eff}) was calculated using the simplified form of Fick's diffusion equation (Demiray and Tulek, 2017). The temperature dependence of moisture diffusivity was described using the Arrhenius equation (Equation 1). Activation energy (E_a, kJ/mol) values were obtained from the plot of ln(D_{eff}) versus the reciprocal of absolute temperature (T, K).

$$D_{eff} = D_0 \exp(E_a/\mathrm{R}T) \qquad (1)$$

where

D_0 is the Arrhenius factor
E_a is the activation energy (kJ/mol)
R is the universal gas constant (8.314 kJ/mol.K)
T is the drying temperature (K).

Mass transfer parameters

The determination of mass transfer properties, Biot number (B_i), and convective mass transfer coefficient (h_m) was calculated as described by Dincer and Hussain (2002). Biot number is a dimensionless parameter that indicates the resistance to moisture diffusion within the product (Toğrul and Toğrul, 2007). Dincer number (D_i) provides the relationship between flow velocity of the drying fluid and drying coefficient of the product (Akpinar and Dincer, 2005).

Hunter whiteness and rehydration index

The hunter whiteness was also calculated using Equation 2 below. The color parameters (L, a, and b values) were determined using a colorimeter (Chromameter CR410, Japan) at 10 difference points.

$$\text{Hunter whiteness} = 100 - \sqrt{a^2 + b^2 + (100 - L)^2} \qquad (2)$$

The rehydration index of moringa powder was determined using the method of Pérez-Won et al. (2023).

Drying Methods Sustainability Parameters

The energy consumption (E_t) was determined using an energy consumption meter (VH-TD-PT, Sinotimer, Shanghai, China). The specific energy consumption (SEC) (kW) was described as the energy required (SEC = E_t/m_w) to remove 1 kg of water from the sample (Thuy et al., 2022a), where m_w is the mass of water removed (kg) (Boateng et al., 2021).

Greenhouse gas emission (GHG) factors

The relevant coefficients are used to calculate the amount of GHGs and pollutants (CO_2, SO_2, NO_x) generated per kWh of electricity emitted by various fossil fuel plants (gas turbines, steam, coal, and hybrid plants) relative to the fuel used, which was calculated following the updated method of Pérez-Won et al. (2023). The estimated cost of the drying process with different fuel types was also determined as described by Pérez-Won et al. (2023).

RESULTS AND DISCUSSION

Drying kinetics of moringa leaves

The drying temperature used for the drying process of moringa leaves has a great influence on the percentage of moisture in the raw materials. Moisture ratio (MR)

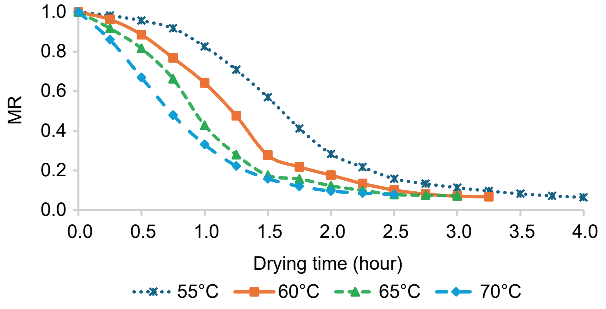

Fig. 1. MR as function of air temperature and drying time

decreased continuously as temperature and time increased (Fig. 1). Many studies have shown that the main factor affecting drying kinetics is the drying air temperature, as has been noted in several studies (Tai et al., 2021; Thuy et al., 2022a; Thuy et al., 2021b). During the drying process, the supply of energy by heating leads to movement of the water inside the food matrix; therefore, a higher drying air temperature produces a higher drying rate and a faster reduction in the percentage of moisture. The final moisture content of moringa leaves reached 5–7% after 4, 3.25, 3, and 2.5 hours, respectively, at the drying temperatures of 55, 60, 65, and 70°C. The drying rate decreased continuously throughout the drying time (Figures 2–3).

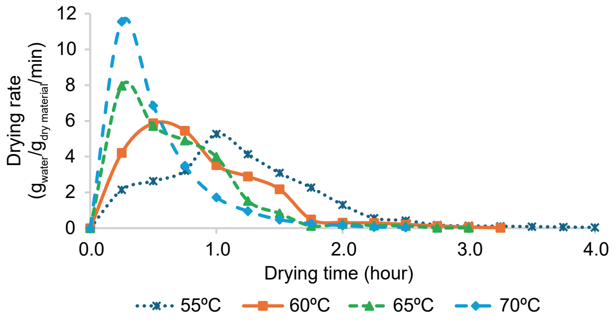

Fig. 2. Drying rate vs drying time at different drying temperatures

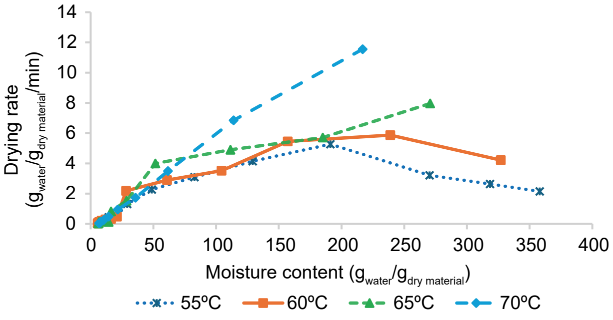

Fig. 3. Drying rate vs moisture content of moringa leaves at different temperatures

No constant speed of rate of drying was observed during the drying process of moringa leaves. At the initial stage, the high drying rate was found and then it reduced in the later stage. These results are in strong agreement with previous studies on herbal leaves by Doymaz et al. (2006). When the temperature increases by 5°C, from 60°C to 70°C, the drying time decreased by 18.75, 17.7, and 16.7%, respectively. The drying time does not decrease equally when the temperature increases at an equal time. The energy provided for the drying process at 70°C is higher than other temperatures, promoting the process of removing water from the material quickly in the early stages. However, as the amount of water gradually decreases, the drying speed may also decrease accordingly. This process can be explained by the fact that at a low temperature, the moisture mobility in the raw material is low. As the drying temperature increases, the mobility increases, thereby increasing the moisture diffusion capacity (Kaya et al., 2007). The percentage of moisture decreased exponentially as the drying time increased. The percentage of moisture continuously decreased, suggesting that diffusion dominated the internal mass transfer (Kaya et al., 2007). These results indicate that diffusion is most likely the physical mechanism governing moisture movement in moringa leaves. The results show that drying temperature is an effective parameter for drying moringa leaves (Zielinska and Markowski, 2010). The higher the temperature, the faster the moisture loss of the material and the shorter the drying time (Tai et al., 2021; Thuy et al., 2022a). Studies show that the drying process of fruits and vegetables follows the described kinetic models and is influenced by the equipment used as well as the type of material (Loan et al., 2023; Thuy et al., 2021b; Thuy et al., 2020).

The most important aspect of drying technology is the mathematical modeling of drying processes and equipment (Gunhan et al., 2005). The recorded moisture content in moringa leaves was converted into the calculated moisture ratio, applied to 7 commonly used thin layer drying models. The results of the statistical analyzes performed on these drying models are given in Table 2. The goodness of fit was

Table 2. Fitting parameters of thin-layer models for drying moringa leaves

Model name	Temp. (°C)	Model constants	RMSE	R^2 (%)	χ^2
Henderson and Pabis	55	a = 1.1943; k = 0.6063	0.1101	91.78	0.0137
	60	a = 1.1482; k = 0.7853	0.0888	94.39	0.0092
	65	a = 1.1128; k = 0.9596	0.0748	95.82	0.0066
	70	a = 1.0621; k = 1.1213	0.0423	98.55	0.0022
Logarithmic	55	a = 1.6317; k = 0.3083; c = –0.4983	0.0891	94.98	0.0096
	60	a = 1.3826; k = 0.4972; c = –0.2781	0.0753	96.30	0.0072
	65	a = 1.1891; k = 0.7836; c = –0.9810	0.0727	96.40	0.0069
	70	a = 1.1007; k = 1.0007; c = –0.0502	0.0421	98.72	0.0024
Newton	55	k = 0.5097	0.1303	87.72	0.0181
	60	k = 0.6873	0.1028	91.84	0.0114
	65	k = 0.8673	0.0833	94.34	0.0075
	70	k = 1.0572	0.0468	98.02	0.0024
Page	55	k = 0.2391; n = 2.1653	0.0396	98.94	0.0018
	60	k = 0.4993; n = 1.7988	0.0370	99.02	0.0016
	65	k = 0.7739; n = 1.5775	0.0442	98.54	0.0023
	70	k = 1.0446; n = 1.2780	0.0265	99.17	0.0009
Two-term	55	a = 0.5971; k = 0.6066; b = 0.5971; k_0 = 0.6059	0.1183	91.78	0.0183
	60	a = 0.5741; k = 0.7844; b = 0.5741; k_0 = 0.7855	0.0972	94.39	0.0132
	65	a = 0.5564; k = 0.9597; b = 0.5564; k_0 = 0.9597	0.0826	95.82	0.0099
	70	a = 0.5311; k = 1.1214; b = 0.5311; k_0 = 1.1214	0.0480	98.55	00036
Modified Henderson and Pabis	55	a = 0.3981; k = 0.6064; b = 0.3981; g = 0.6063; c = 0.3981; h = 0.6062	0.1286	91.78	0.0198
	60	a = 0.3827; k = 0.7853; b = 0.3827; g = 0.7853; c = 0.3828; h = 0.7856	0.1087	94.39	0.0207
	65	a = 0.3710; k = 0.9593; b = 0.3710; g = 0.3710; c = 0.3709; h = 0.9600	0.0937	95.82	0.0163
	70	a = 0.3540; k = 1.1218; b = 0.3540; g = 1.1219; c = 0.35404; h = 1.1204	0.0568	98.55	0.0071
Wang and Sign	55	a = –0.3578; b = 0.02575	0.0983	93.46	0.0109
	60	a = –0.5149; b = 0.0654	0.0371	95.84	0.0016
	65	a = –0.6796; b = 0.1226	0.0636	96.97	0.0048
	70	a = –0.8333; b = 0.1873	0.0272	99.40	0.0009

determined using the correlation coefficient (R^2), mean error (RMSE), and Chi-squared (χ^2). Criteria to choose the best model to describe the drying process of moringa leaves are based on the highest correlation coefficient of determination (R^2), lowest mean error (RMSE), and Chi-squared value (χ^2) (Demir et al., 2004). All equations give high R^2 values in the range of 0.87 to 0.99, RMSE ranges from 0.0265 to 0.1303, and χ^2 ranges from 0.0009 to 0.0207, indicating that all equations can adequately describe the drying rate of moringa leaves.

The obtained results show that the Page model has a higher compatibility (at all the drying temperatures performed) than the other models, with the correlation coefficient of determination in the range of 98.54 to 99.17%. The lowest χ^2 and RMSE values (0.009 and 0.0265, respectively) were observed in the Page model over the defined temperature range.

Diffusion coefficient and activation energy

Effective moisture diffusion coefficient (D_{eff}) when drying moringa leaves at 55, 60, 65, and 70°C has the D_{eff} value of 8.36×10^{-12} m^2/s, 9.85×10^{-12} m^2/s, 1.09×10^{-11} m^2/s, and 1.22×10^{-11} m^2/s (Table 3). D_{eff} increases with increasing drying temperature, and drying at 70°C gives the highest D_{eff} value, which is in the general range for drying food ingredients. The variation in the values of the effective diffusivity could be due to the drying conditions, meaning that the effective diffusivity depends on the drying temperature (Alara et al., 2019). Air temperature was correlated with the energy supply for water molecules moving out of the food matrix. Therefore, high temperatures could enhance the movement of water molecules and lead to a faster drying time. The activation energy was found to be 20.14 kJ/mol; this result is higher than the study of Premi et al. (2012). The activation energy for drumstick leaves is 12.50 kJ/mol. The value of activation energy for most agro-food products is in the range of 12.7–110 kJ/mol (Thuy et al., 2022b). A lower activation energy indicates a lower sensitivity to temperature (Tai et al., 2021; Thuy et al., 2022a; Thuy et al., 2022b). The values of the B_i number, which ranged from 3.302 to 5.740, were found to increase as the temperature rose. A similar pattern was noted for vacuum-dried apples, which increased in temperature from 50°C to 70°C (Nadi and Tzempelikos, 2018). The mass transfer coefficient (h_m) also ranged from 1.59×10^{-9} to 5.37×10^{-9} m/s when the drying temperature was increased. This demonstrates that greater drying temperatures can achieve a higher rate of moisture transfer. Higher mass transfer rates come from drying at higher temperatures because it increases the sample's available heating energy and increases the activity of water molecules (Tarafdar et al., 2021). The rehydration index ranged from 9.12–12.54%, which also indicated that hot air drying led to the food matrix collapsing and a reduction in the capacity of water absorbance. It was also reported that after hot air drying the rehydration index could not exceed 13% (Aravindakshan et al., 2021).

The color of moringa powder also changed as a function of the drying temperature. The increase of *HW* value was found when the temperature rose. The shorter time and higher temperatures reduced the browning reaction and browning enzyme activity; therefore, the color of the product was maintained (Cernîşev, 2010). However, at a mild-temperature of 55°C, the activation of the polyphenol oxidase led to

Table 3. Drying behaviors, mass transfer parameters, rehydration ratio and hunter whiteness

Temp. (°C)	k	D_{eff}	B_i	h_m 10^{-9} m/s	RH %	*HW*	SEC kWh/kg
55	0.2931^{a}	8.36×10^{-12}	3.302^{a}	1.59^{a}	12.54^{c}	61.23^{c}	54.01^{c}
60	0.4993^{b}	9.85×10^{-12}	4.352^{b}	2.23^{b}	11.56^{bc}	68.74^{b}	46.07^{b}
65	0.7793^{c}	1.09×10^{-11}	5.142^{c}	3.45^{c}	10.52^{ab}	74.84^{a}	41.38^{a}
70	1.0446^{d}	1.22×10^{-11}	5.740^{d}	5.37^{d}	9.12^{a}	74.32^{a}	39.92^{a}

The same letter in a column indicates no significant difference ($p > 0.05$).

Table 4. Greenhouse gas (GHG) emissions kg/kg water by different energy sources

Temperature (°C)	Steam		Gas-turbine		Combined-cycle	
	natural gas	heavy oil	natural gas	heavy oil	natural gas	heavy oil
CO_2						
55	34 350.36	55 360.25	42 235.82	56 602.48	24 304.50	33 594.22
60	29 300.52	47 221.75	36 026.74	48 281.36	20 731.50	28 655.54
65	26 317.68	42 414.50	32 359.16	43 366.24	18 621.00	25 738.36
70	25 389.12	40 918.00	31 217.44	41 836.16	17 964.00	24 830.24
SO_2						
55	0	825.27	0	207.40	0	120.44
60	0	703.95	0	176.91	0	102.74
65	0	632.29	0	158.80	0	92.28
70	0	609.98	0	153.29	0	89.02
NO_x						
55	145.29	136.11	103.16	312.72	159.33	204.16
60	123.93	116.10	87.99	266.75	135.91	174.14
65	111.31	104.28	79.04	239.59	122.07	156.42
70	107.38	100.60	76.25	231.14	117.76	150.90

a darkening of moringa powder (Szczepańska et al., 2020).

Specific energy consumption and GHG emission factors

One of the key characteristics of evaluation during process activities, such as drying and distillation, is energy consumption. Energy prices continue to rise and fluctuate due to a lack of fossil fuels and environmental issues (greenhouse gas emissions), necessitating the development of innovative ways to reduce energy use in industry (Mierzwa et al., 2019). Table 3 also presents the effect of different temperatures on the specific energy consumption (SEC) of the hot air dryer. As expected, by increasing the temperature, the drying time and SEC were reduced because the thermal gradient and accelerating moisture extraction were enhanced. That is, drying at higher temperatures caused larger mass transfer and thus a shorter drying time, which reduces SEC (Filippin et al., 2018). The highest SEC (54.01 kWh/kg) occurred at 55°C. However, its lowest amount (39.92 kWh/kg) was reported at 70°C. Based on greenhouse gas emissions of power plants using natural gas and heavy oil for production of 1 kW of electricity (Nazari et al., 2010), the lowest emissions were seen when moringa leaves were dried at 70°C and 0.5 m/s (Table 4). By increasing the inlet air temperature, their emission levels started to decline. The increase in GHG emissions can be explained by the higher SEC during drying at a high air velocity and a low temperature (Motevali and Tabatabaee Koloor, 2017; Thuy et al., 2022a).

CONCLUSIONS

The drying model's application revealed that it is useful for describing the trend of moisture content of moringa leaves at different temperatures. The Page model demonstrated the highest agreement with the experimental value among the seven applicable models. The physical appearance of the product, rehydration capacity, and the amount of energy used are both significantly impacted by the change in drying temperature. The findings indicate that drying moringa leaves at 65–70°C was the most effective temperature to maintain the quality as well as reduce gas emissions. To preserve product quality while simultaneously saving energy and contributing to lessening environmental pollution, it is necessary to conduct a more thorough analysis of the process parameters to optimize the production process.

DATA AVAILABILITY

Datasets from the current study are available from the corresponding author upon request.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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