Mathematical modelling of the performance of an impact snake gourd (*Trichosanthes cucumerina*. L) seed sheller

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Abstract: A mathematical model for the prediction of shelling efficiency of an impact snake gourd seed decorticator was presented using dimension analysis based on the Buckingham's pi theorem. Experimental verification of the models was conducted comparing the theoretical predictions with estimates from the representation of conventional methods. A high coefficient of determination was found between the predicted and the experimental value (98.45% for effect of moisture content on decortication efficiency; 99.69% for effect of hammer diameter on decortications efficiency and 97.35% for effect of hammer speed on the decortications efficiency) showing that the model is appropriate.

Keywords: dimension analysis, model equation, decortication efficiency, moisture content, hammer diameter, hammer speed

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1 Introduction

The snake gourd (*Trichosanthes cucumenina* L) commonly called snake tomato in Nigeria belongs to the botanical family *cucurbitacea*. It is widely distributed all over the world with about 70 general and over 700 species (Robinson and Decker- Walters, 1997). The fruit is long with deep green background (Onagoruwa, 2002). The flowers are monoecious (individual flowers are either male or female, but both sexes can be found on the same plant) and are pollinated by insects.

Snake gourd fruit (Figure 1) which contains oilseed (Figure 2) is a valuable source of oil, protein, fat and vitamins. It has been reported by Adebooye et al. (2005) that the seed is a good source of nutrients containing crude protein (26.2-26.6 g 100 g^{-1}), fat (44.6-57.2 g 100 g^{-1}), phosphorous (78.0-81.5 g 100 g^{-1}) and calcium (41.0-46.7 g 100g^{-1}) while the fruit pulp is a good source of ascorbic acid (23.1-23.3 mg 100 g^{-1}). The oil content of the seed was found to be between 34% and 57% (Idowu, 2015). It is a biannual climber crop growing to 5 m at a fast rate. The plant could be planted twice in a year in an area with bimodal rainfall like the western Nigeria (Oloyede and Adebooye, 2005).

The general demand for fats and oils increases with increasing population through discovery of new uses (Omotojesi et al., 2011). Anonymous (2008) estimated the annual vegetable oils and fats required in Nigeria for food and non- food uses as 1,722,000 tons whereas the annual production is 1,138,000 tons. Thus about 585,000 tons of vegetable oil must be imported annually to argument the short fall.

Figure 1 Snake gourd fruit (LAUTECH Agric. Engr. Farm)

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Figure 2 Snake gourd seeds (LAUTECH Agric. Engr. Farm)

With the increase in demand for vegetable oils which yield valuable product used in the manufacturing of many products, namely, building auxiliaries, candles, cleaning agents, cosmetics, detergents, fire-extinguishing agents, flotation agent, food emulsifiers, insecticides, lubricants, paints, paper production, pharmaceuticals etc. The global demand for vegetable oil has far exceeded production. It is becoming increasingly difficult to meet world's demand for vegetable oil from traditional source of available oilseed, and it is evident that acceptability of any oilseed for industrial use depends on the availability of appropriate technology for processing it. Shelling has been identified as a major bottle neck in recommending snake gourd seed for large scale production. It has been confirmed that the seed contains about 55% oil (Idowu, 2015) which is a good percentage compared with other oil seeds reported (Anonymous, 1995). Currently, shelling of snake gourd seed as a preparatory step for oil extraction is done manually. Traditional (manual) method of shelling snake gourd seed is slow, time consuming, tedious, inefficient and energy-sapping which discourage higher productivity. Therefore, to encourage mechanization of the crop and its industrial utilization, a shelling machine is essential.

Processing of snake gourd seed include washing, drying, shelling, cleaning and oil extraction. The traditional method of shelling snake gourd seed has been identified has a major obstacle to the mechanisation of the crop, thus limiting the availability of the product for industrial purpose. The low interest in industrial utilization of snake gourd seed is a result of lack of shelling technology of the seed. Research has identified vegetable oil produced from unshelled seed to have low quality and quantity. Therefore to encourage the production of this very important but neglected crop, the development of a shelling machine will go a long way in encouraging investment on snake gourd seed oil extraction. A shelling machine has been designed and its efficiency needs to be optimized. The present study was undertaken to establish a mathematical model for predicting the shelling efficiency of an impact snake gourd sheller using dimension analysis.

2 Development of the impact shelling model

Mathematical modelling is generally understood as a process of applying mathematics to a real word problem with a view to understand the latter. Modelling the shelling efficiency of a decorticating machine involves understanding the processes which include all actions from the hopper through the shelling chamber to the collector chute (Ndukwu and Asoegwu, 2011). Shelling processes involves dependent variables, which are functions of several independent variables. It has been established that shelling efficiency depends on some seed parameters (Table 1) and machine characteristics (Table 2). These two categories of parameters are combined in modelling the shelling efficiency of the snake gourd seed using dimension analysis.

Table 1 Crop parameters affecting efficiency of Agricultural crops

S/N	Crop parameter	Source
i	Moisture content	Liang et al. (1984); Ezeike (1986); Simonyan et al. (2006); Oluwole and Adedeji (2012); Gitau et al. (2013)
ii	Variety	Xavier (1992); Koyuncu et al. (2004); Simonyan et al. (2006); Jha et al. (2010)
iii	Seed size	Liang et al. (1984)
iv	Percentage of matured nuts	Liang et al. (1984)
v	Seed weight	Idowu and Owolarafe (2014)
vi	Seed volume	Idowu and Owolarafe (2014)

Table 2 Machine characteristics affecting shelling efficiency of Agricultural crop

S/N	Machine Characteristics	Source
i	Hammer speed	Liang et al. (1984); Ezeike (1986); Simonyan et al. (2006); Tiwari et al. (2010); Gitau et al. (2013)
ii	Hammer radius	Xavier (1992); Koyuncu et al. (2004); Simonyan et al. (2006); Jha et al. (2010)
iii	Throughput	Liang et al. (1984); Rothang et al. (2003)
iv	Percentage of matured nuts	Liang et al. (1984)

Dimensional analysis was chosen for the mathematical modelling because it offers a method for reducing complex physical problems to the simplest and the most economical form prior to obtaining a quantitative answer. It has been reported that when several variables are involved and boundary conditions are not completely articulated the best option for mathematical modelling is dimension analysis (Aleksander, 2015). With ten variables involved (Table 1 and 2) the principle of dimensional analysis using the method of Buckingham's Pi theorem was adapted for the mathematical modelling.

The Buckingham's pi theorem provides a method for computing sets of dimensionless parameters from given variables, even if the form of the equation remains unknown. It also describes the relation between the number of variables and fundamental dimensions. This theorem states that the total number of these relevant dimensional parameters (n) can be grouped into n-m independent dimensionless groups. The number m is usually equal to the minimum of independent dimensions required to specify the dimensions of all relevant parameters. This method has been used by Ndukwu and Asoegwu (2011) to mathematically modell the prediction of the cracking efficiency of a vertical-shaft centrifugal palm nut and Simonyan et al. (2006) for the modelling of the grain cleaning process of a stationary sorghum thresher.

2.1 Assumptions for the model development

Tables 1 and 2 show about ten independent variables that can influence the efficiency of the machine and using all may make resulting model too complex. To reduce the independent variables to a manageable level the following assumptions were made:

i) Only one variety of the seed is considered;

ii) The seed size is constant at the same moisture content;

iii) The moisture content of the seed and kernel does not change during the process;

iv) The radius of the shelling chamber is fixed during shelling;

v) The weight and volume of the seed are constant at a particular moisture content;

vi) Cracking speed is the same as the shaft speed;

vii) Shaft speed is constant; and

viii) Shelling chamber's dimension is constant.

The above assumptions have reduced the major independent variables to six as shown below:

a) Seed moisture content, θ, (%);

b) Bulk density of the seed, ρ_b, (kg m^{-3});

c) Seed density, ρ_t, (kg m^{-3});

d) Feed rate, F_{sr}, (kg s^{-1});

e) Hammer speed, v_H, (m s^{-1});

f) Hammer radius, R_H, (m).

2.2 Modeling the shelling of snake gourd seed using dimension analysisvH

A mathematical model, using dimensional analysis, was used to characterize the shelling of snake gourd seed. This dimensional analysis has been used to model various physical systems. Simonyan et al. (2006) used the dimensional analysis for modelling cleaning process of a thresher while Ndukwu and Asoegwu (2011) use the analysis for modelling cracking efficiency. Buckingham's pi theorem of dimensional analysis was used to model the shelling efficiency of the snake gourd shelling machine.

The mathematical expression for the shelling efficiency (η) as a function of those selected independent variables is as shown in Equation (1).

$$(\eta) = f(\theta, \rho_b, \rho_t, F_{sr}, v_H, R_H) \quad (1)$$

where, θ = Seed moisture ratio; ρ_b = Bulk density of the seed; ρ_t = Seed density; F_{sr} = Feed rate; v_H = Hammer speed; R_H = Hammer radius.

The fundamental dimensions present in the variables selected are three as presented in Table 3. They were used in the derivation of the shelling efficiency. The dimensions of the physical quantity (independent variables) selected are expressed in terms of the fundamental dimensions as shown in Table 4. The variables and their corresponding dimensions used in the modelling of shelling efficiency of snake gourd seed decorticator are as presented in Table 5. Table 6 shows the dimension matrix of the chosen independent parameters. From Table 5 only θ is a dimensionless constant among the independent variables; hence it is excluded from the dimensionless terms determination exercise, and then introduced after the other terms were formed (Ndukwu and Asoegwu, 2011). To estimate the numbers of Pi dimensionless equations to be solved, the number of units must be subtracted from the number of independent parameters. One of the laws of Buckingham's pi theorem states that "the number of dimensionless and independent quantities required to express a relationship among variables in any phenomenon is equal to the number of quantity involved minus the number of dimensions in which those quantities may be measured" (Murphy, 1950; Simonyan et al., 2006; Ndukwu and Asoegwu, 2011). Since the number of identified independent variables that determined the shelling efficiency is 6 and the number of fundamental units is 3; therefore the number of pi equations is 3. It follows that π_1, π_2 and π_3 are the three pi equations required.

Table 3 Fundamental unit used in the model

S/N	Dimension	Symbol	MKS-Unit
i	Length	L	m (meter)
ii	Mass	M	kg (kilogram)
iii	Time	T	s (second)

Table 4 Selected parameters and their corresponding dimensions

S/N	Variables	Symbol	Unit	MKS-Dimensions
i	Seed moisture ratio	θ	%	$M^0 L^0 T^0$
ii	Bulk density of the seed	ρ_b	kg m^{-3}	$M^1 L^{-3} T^0$
iii	Seed density	ρ_t	kg m^{-3}	$M^1 L^{-3} T^0$
iv	Feed rate	F_{sr}	kg s^{-1}	$M^1 L^0 T^{-1}$
v	Hammer speed	v_H	m s^{-1}	$M^0 L^1 T^{-1}$
vi	Hammer radius	R_H	m	$M^0 L^1 T^0$

Table 5 Dimension matrix of the variables

	η_s	θ	ρ_t	ρ_b	F_{sr}	v	R
M	0	0	1	1	1	0	0
L	0	0	–3	–3	0	1	1
T	0	0	0	0	–1	–1	0

Table 6 Model validation using effect of moisture content on the snake gourd decorticating efficiency

S/N	Moisture ratio	Measured Efficiency (Mean±SD %)	Predicted efficiency, %
1	0.06	87 ±4.3	96.12
2	0.08	84 ±3.6	75.11
3	0.1	78 ±3.4	65.57
4	0.12	55 ±2.5	48.1
5	0.15	42 ±2.3	38.0

The grouping of variables to form the pi terms for the shelling efficiency is as presented in Equation (2) while the corresponding dimensional equation is as presented in Equation (3).

$$\eta_s^a = \rho_b^b ; \rho_t^c ; F_{sr}^d ; v_H ; R_H^f = 0 \tag{2}$$

Where all the symbols are as represented in Table 4

$$[M^0 L^0 T^0]^a = [M^1 L^{-3} T^0]^b \quad [M^1 L^{-3} T^0]^c$$
$$[M^1 L^0 T^{-1}]^d \quad [M^0 L^1 T^{-1}]^e \quad [M^0 L^1 T^0]^f \tag{3}$$

2.3 Selection of repeated variables

The three repeating variables selected are ρ_t, F_{sr} and R_H since the combination cannot form a dimensionless group.

The dimensions of these variables are as presented in Equations (4), (5) and (6)

$$\rho_t = \frac{M}{L^3} \tag{4}$$

$$F_{sr} = \frac{M}{T} \tag{5}$$

$$R_H = L \tag{6}$$

Then rewriting the dimensions in terms of the variables

$$M = \rho_t L^3 \tag{7}$$

$$T = \frac{\rho_t R_H{}^3}{F_{sr}} \tag{8}$$

$$L = R_H \tag{9}$$

The Buckingham's pi is then formed by taking each of the two remaining non repeating variables ρ_b and v_H in turn.

$$\Pi_1 = \frac{\rho_t}{\rho_b} \tag{10}$$

$$\Pi_2 = \frac{R_H{}^2 v_H \rho_t}{F_{sr}} \tag{11}$$

$$\Pi_3 = \theta \tag{12}$$

The functional equation for describing the shelling efficiency involving dimensionless terms is as presented in Equations (13) and (14).

$$\eta_s = f(\Pi_1, \Pi_2, \Pi_3) \tag{13}$$

$$\eta_s = f\left(\frac{\rho_t}{\rho_b}, \frac{R_H{}^2 v_H \rho_t}{F_{sr}}, \theta\right) \tag{14}$$

These dimensionless pi terms were combined so as to have one representing equation as presented in Equation (15).

$$\Pi_1 \times \Pi_2 \times \Pi_3^{-1} = \frac{\rho_t}{\rho_b} \times \frac{R_H{}^2 v_H \rho_t}{F_{sr}} \times \theta^{-1} \qquad (15)$$

Hence the shelling efficiency of the machine can be defined as in Equation (16).

$$\eta_s = \frac{\rho_t{}^2 v_H R_H{}^2}{\rho_b F_{sr} \theta} \qquad (16)$$

2.4 Determination of validation parameters

Six parameters appeared in the shelling efficiency equation. These parameters were determined using standard methods.

2.4.1 The true density and the bulk density determination

Idowu and Owolarafe (2012) reported the determination of bulk and true density of the seed. They measured the true density of the seed by the method of water displacement while the bulk density was determined by filling a 500 mL beaker with seeds dropped from a height of 150 mm and the container tapped ten times. They reported the mathematical relationship between the moisture content and the true density (Equation (17)) and the bulk density (Equation (18)). These equations were used in estimating the two densities at the selected moisture content.

$$\rho_{TS} = 0.01 m_c + 0.998 \qquad (17)$$

$$\rho_{Bs} = 0.007 m_c + 0.329 \qquad (18)$$

where, ρ_{TS} is true density; ρ_{Bs} is bulk density and m_c is the moisture content.

2.4.2 Moisture content determination

The validation of the model was done at four moisture content. The method of Idowu and Owolarafe (2012) was used to obtain different moisture content.

Feed rate (Frs) (kg h^{-1})

Approximate feed rate was calculated as weight of snake gourd seed fed into the machine per unit time (hr.). The Equation below was adapted.

$$F_{rs} = \frac{WT}{t} \quad \text{(Ndukwu and Asoegwu, 2011)} \qquad (19)$$

where, WT is weight of the snake gourd seed (kg); t is time taken to empty the whole seed into the shelling chamber (h).

2.4.3 Shelling speed

Linear velocity for the shelling hammer is calculated using Equation (20).

$$V = \frac{2\pi r N}{60} \qquad (20)$$

where, N is angular speed of the shelling hammer; R is radius of the pulley (m); V is linear velocity (m s^{-1}).

2.4.4 Shelling efficiency (η)

This is the ratio of the mass of completely shelled and unshelled snake gourd seed to the total mass of the seed feed into the hopper.

$$CE(\eta) = \frac{WT - X}{WT} \qquad (21)$$

where, WT = total weight of the snake gourd seed feed into the hopper (kg); X = weight of partially cracked and unshelled seed (kg)

2.5 Snake gourd seed decorticator test rig configuration

The snake gourd seed decorticator test rig prototype that was specially developed for the experiment is as shown in Figure 3. The test rig consists of hopper, decorticating drum which house the decorticating hammer and the frame. The snake gourd seeds were fed into the hopper manually. The feeding time was recorded using stop watch. Impact force was used by the hammer to decorticate the seed. The decorticated kernel, the seed and the chaff were then collected and weighed.

3 Results and discussions

The mathematical model developed (Equation (22)) for the impact snake gourd decorticator was validated using an experimental data generated for the purpose. The model validation was done at four moisture content, three shelling speed and three hammer diameters as discussed below

3.1 Model validation using the effect of moisture ratio on the efficiency of the decorticator

The model was validated using Microsoft Excel 2007 statistical package using statistical analysis based on general linear model (GLM). The predicted and the experimental shelling efficiency are presented in Table 6. The results showed that as the moisture ratio is increasing in both measured and predicted, the efficiency was decreasing. This result was in agreement with Ndukwu and Asoegwu (2011) who also reported a decrease in melon shelling machine efficiency as the moisture content is increasing.

Figure 3 Snake gourd seed decortications machine test rig

Figure 4 shows that the graph of the predicted and the experimental are closely parallel. The plot of predicted value against the experimental value (Figure 5) shows a very high correlation with R^2=0.9845. The regression equation that represents the relationship between the predicted and the experimental is as presented in Equation (23).

$$PSE = -14.3ME + 107.3 \quad (R^2 = 0.9845) \tag{23}$$

where, *PSE* is predicted shelling efficiency (%); *ME* is measured efficiency (%).

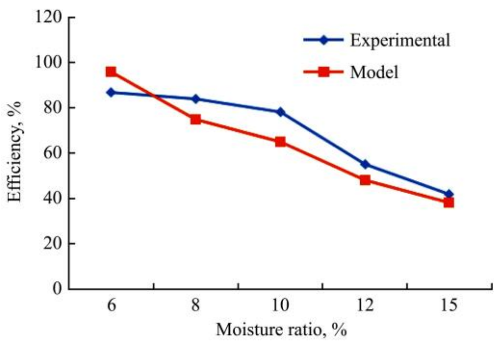

Figure 4 Effect of moisture ratio on the efficiency of the decorticating machine using experimental method and the model

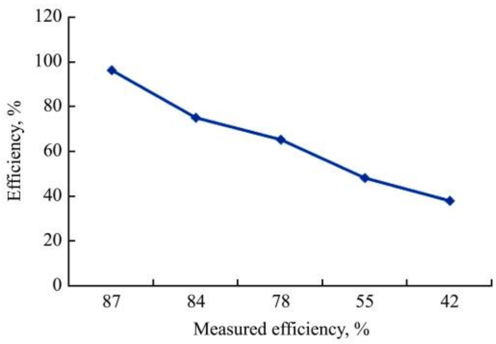

Figure 5 A plot of model prediction against the measured efficiency

3.2 Model validation using the effect of hammer diameter on the efficiency of the decorticator

The model was validated using three different hammer diameters. All other parameters like seed density, seed bulk density, hammer speed and feed rate are kept constant. Table 7 showed the effect of the hammer diameter on the decortication efficiency of the machine. This result showed that as the hammer diameter increased the decortications efficiency also increased. These results were in agreement with the report of Okonko et al. (2010) on melon shelling and Kassim et al. (2011). The results of the measured and the predicted decortications efficiency shows an increase in decortication efficiency as the hammer diameter increased. Figure 6 showed the relationship of the measured and the predicted decortications efficiency with the hammer diameter, showing two parallel graphs. Figure 7 shows the plot of predicted efficiency with the measured efficiency. The relationship between the two shows a good correlation. The mathematical relationship between the measured efficiency and the predicted efficiency using the effect of hammer diameter is as presented in Equation (23).

$$MSE = 15.5\ PSE + 49 \quad (R^2 = 0.9969) \tag{23}$$

where, *MSE* is Predicted shelling efficiency (%); *ME* is measured efficiency (%).

Table 7 Model validation using effect of hammer diameter on the snake gourd decortication efficiency

S/N	Hammer diameter, mm	Measured efficiency, %	Predicted efficiency, %
1	115	65±2.1	54.0
2	135	79±3.2	75.0
3	150	96±4.3	93.0

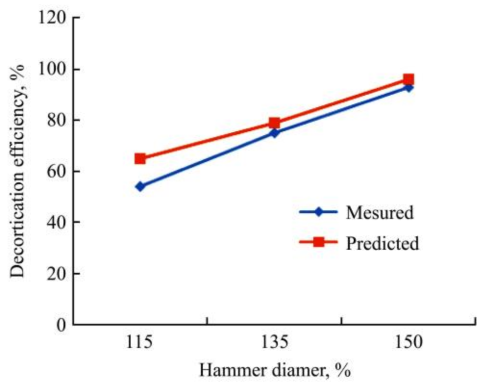

Figure 6 Effect of the hammer diameter on the efficiency of the decortication machine

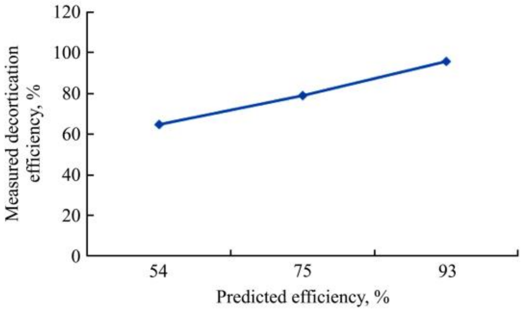

Figure 7 Plot of predicted efficiency against measured efficiency

3.3 Model validation using the effect of hammer speed on the efficiency of the decorticator

The model was validated using effect of speed on the decortications efficiency of the snake gourd decortications efficiency. The predicted and the measured shelling efficiency are presented in Table 8. The results showed that as the hammer speed was increasing both the measured and the predicted efficiency was also increasing. Okonkon et al. (2010) reported an increase in shelling efficiency for melon when the impeller speed increased. Figure 8 shows that the graph of the predicted and the experimental are closely parallel. The plot of predicted value against the experimental value (Figure 9) shows a very high correlation with $R^2 = 0.9735$. The regression equation that represents the relationship between the predicted and the experimental is as presented in Equation (24). Hence the two tests showed that the results of the predicted model are not significantly different from the results measured.

Table 8 Model validation using effect of hammer speed on the snake gourd decorticating efficiency

S/N	Hammer speed, m s^{-1}	Measured efficiency, %	Redicted efficiency, %
1	3.61	87.2±2.3	79.0
2	4.13	92.1±3.1	90.7
3	4.42	95±3.6	97.2

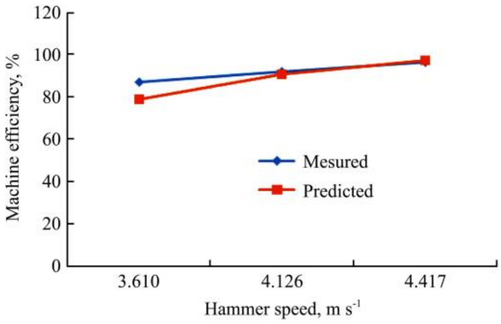

Figure 8 Effect of hammer speed on both measured and predicted efficiency

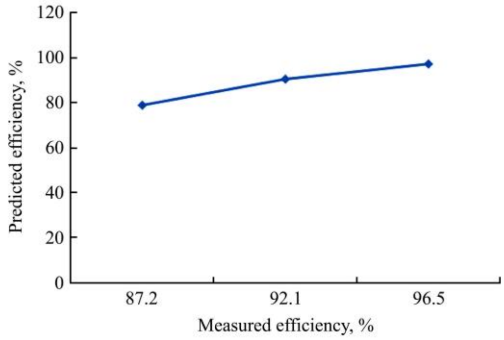

Figure 9 A plot of measured efficiency against predicted efficiency of the machine

$$PSE = 9.1\mathrm{ME} + 70.77 \ (R^2 = 0.9735) \qquad (24)$$

where, *MSE* is predicted shelling efficiency (%); *ME* is measured efficiency (%).

4 Conclusions

Decortication efficiency of snake gourd seed was mathematically modelled using dimension analysis based on the Buckingham's pi theorem. A functional relationship between some machine parameters (hammer diameter, hammer speed and feeding rate) and crop parameters (seed bulk density, seed true density and seed moisture content) were established. The developed model was verified by comparing the predicted with measured results from a snake gourd decorticating test rig. The developed model gave good prediction of decortication efficiency that was not significantly different from the one obtained from measured efficiency.

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