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Empirical Model for Estimation of Soil Permeability Based on Soil Texture and Porosity

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ABSTRACT

Soil permeability is the ability of the soil to pass water or air. Soil permeability is affected by texture, structure, and soil porosity. This study aims to develop a mathematical model to predict the value of soil permeability as a function of the percentage of the constituent fraction of the soil and soil permeability as a function of porosity. The study used soil taken from 7 different locations, with 6 samples for each location, 4 samples for model building and 2 samples for model validation. Parameters observed consisted of the percentage of sand (x1), the percentage of silt (x2), the percentage of clay, (x3), soil porosity (x4) and soil permeability (y). From the analysis, the empirical model obtained is soil permeability as a function of the percentage of constituent fractions of the soil which is expressed by the equation $y_1=36.796 -16.022x_2-23.938x_3$ *and soil permeability as a function of porosity is expressed by the equation* $y_2=12+0.65(x_4-0.06)^{-2.92}$. *The permeability equation as a function of soil constituent fraction (y1) can predict soil permeability with a value of R2 = 0.925 and an RRMSE value of 5.461%, better than the permeability equation as a function of porosity.*

1. INTRODUCTION

Soil, water and air are natural resources that are very important in agriculture. For plants, soil acts as a medium for growth and production. As a growing medium for plants, the ability of the soil will be optimal if it is supported by good physical, chemical and biological conditions (Arifin, 2010). Plant growth depends not only on the availability of chemical materials as elements needed by plants, but also requires water, air and temperature under certain conditions so that the mechanism for the process of utilizing these nutrients by plants occurs (Mawardi, 2011). The physical properties of the soil related to the movement of air and water in the soil are soil porosity and permeability.

Soil porosity is a functional space that connects the soil body with its environment (Lal & Shukla, 2004). Soil pores play an important role in determining the physical, chemical and biological properties of soil (Munkholm *et al*., 2012; Oorts *et al*., 2007; Pagliai *et al*., 2004; Sleutel *et al*., 2012; Smucker *et al*., 2007). Soil physical and chemical processes that do not occur inside the particles or on the soil surface occur in the soil pore spaces (spaces between particles). It is in the soil pore space that air, water, and biological waste products and nutrients are transmitted from one place to another in the soil (Mawardi, 2011). Pore characteristics describe the number, size, distribution, continuity and stability of soil pores (Kay, 1990). Soil porosity is influenced by soil texture, structure, and organic matter content. The relationship between porosity and soil texture can be expressed in the form of an Artificial Neural Network model (Suharyatun *et al*., 2019). In sandy soils, soil porosity is dominated by macro pores which function as water traffic so that infiltration increases. Whereas in clay soils, micro pores play a more important role and the water conductivity is low so that infiltration decreases (Soepardi, 1983).

Soil permeability is the ability of the soil to pass water under saturated conditions (Dariah *et al*., 2006). Quantitatively soil permeability/hydraulic conductivity is the velocity of movement of a liquid in a porous medium and is defined as the velocity of water passing through the soil in a certain period of time expressed in centimeters per hour (Foth, 1991). Soil permeability is affected by the texture, structure and porosity of the soil. Permeability can affect the level of soil fertility because it includes how water, organic matter, mineral matter, air, and other particles are carried with the water into the soil (Rohmat, 2009).

Multiple linear regression is an equation model that describes the relationship of one dependent variable (y) with two or more independent variables (x1, x2,…xn). Multiple linear regression tests are used to predict the value of the dependent variable (y) if the values of the independent variables are known (Yuliara, 2016). The use of multiple linear regression can be used to estimate rice productivity with independent variables: production, harvested area, planted area, average rainfall, and average rainy days (Padilah & Adam, 2019). The use of multiple linear regression is also used to predict the income of coconut farmers in Beo Village, Beo District, Talaud Regency (Mona *et al*., 2015), predict the population in Gunung Malela District (Sinaga *et al*., 2022), and predict the amount of heat exchanger production (Sulistyono & Sulistiyowati, 2018).

Multiple linear regression is easy to apply because it can be operated on simple software such as Microsoft Excel and SPSS. The relationship between texture and soil permeability can be expressed in the form of multiple linear regression equations with the independent variable the percentage of particles making up the soil consisting of the sand fraction, silt fraction and clay fraction.

The development of the power function can be used to predict the value of a parameter close to the observed value (Pinchuk & Kuzmin, 2019). The power function can be analyzed simply using excel software. By using a modification of the power function, it is possible to express the relationship between porosity and soil permeability in the form of a prediction equation.

This study aims to use multiple linear equations to create an empirical model of the relationship between texture and soil permeability and the power function to create an empirical model of the relationship between porosity and soil permeability.

2. MATERIALS AND METHODS

2.1. Material

The materials used in the study were soil taken from 7 different locations with different land uses, namely (1) rubber plantations (Integrated Field Laboratory, University of

Lampung), (2) cassava plantations (Kotabaru), (3) cocoa plantations (BPP), (4) corn field (Tanjung Bintang), (5) corn field (Polinela), (6) sugarcane plantation (PTPN) and (7) chili field (Gisting). Each location was sampled with 6 replications. Theese locations were selected to take the soil samples with the aim of obtaining varying values of soil fraction (texture), porosity, and soil permeability.

Soil sampling was carried out destructively and non-destructively. Destructive sampling of soil was carried out to measure the texture and specific gravity of the soil. Non-destructive sampling of soil used a ring sample with dimensions of diameter f = 7.63 cm and height *L* = 4 cm. Non-destructive samples were used to measure soil permeability and soil volumetric weight.

2.2. Research Implementation

The research was carried out in several stages as presented in the flowchart in Figure 1.

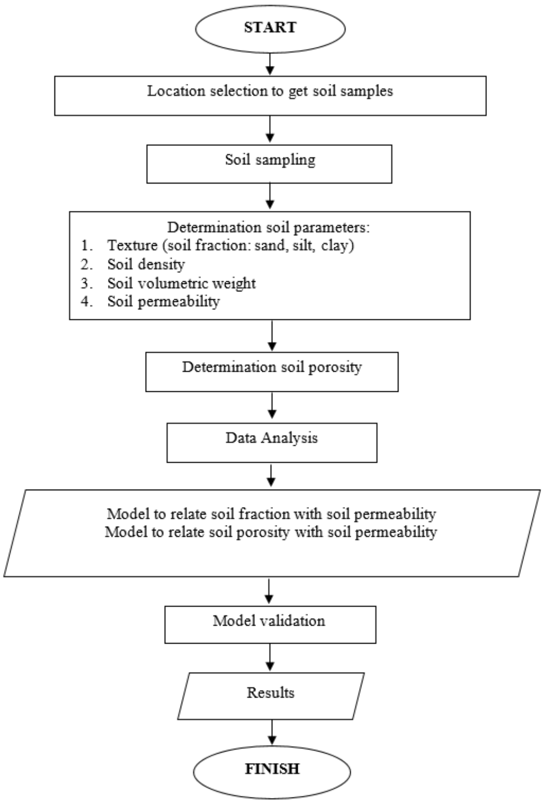

Figure 1. Flow chart for soil permeability research

2.3. Model Development

The empirical model of the relationship between soil constituent fractions and permeability was developed using multiple linear regression and was presented in the form of the equation:

$$y_1 = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \qquad (1)$$

where y_1 is soil permeability (cm/h), x_1 is sand fraction (%), x_2 is silt fraction (%), x_3 is clay fraction (%), and a, b_1, b_2, b_3 were constants.

The non-linear empirical model for the relationship between porosity and permeability is obtained from the development of the power function (Haryanto *et al*., 2020; Pinchuk & Kuzmin, 2019) and is expressed in the form of an equation:

$$y_2 = A + B.(x_4 - C)^N \tag{2}$$

where y_2 is soil permeability as a function of soil porosity (cm/h), x_4 is soil porosity (cm/h), and A, B, C, and N are constants.

2.4. Parameters and Measurements

1. Soil texture

Soil texture were measured using the hydrometer method in the Soil Physics Laboratory, Lampung State Polytechnic. The measurement was carried out to obtain the percentage of soil constituent fractions consisting of sand fraction (x_1), silt fraction (x_2) and clay fraction (x_3).

2. Soil porosity (x_4)

Soil porosity was determined based on the bulk density (r_s) and volumetric weight (r_b) of the soil. The bulk density (r_s) of the soil was determined using the pycnometer method. The tools and materials consisted of a pycnometer (50 ml), rinse bottle (500 ml), thermometer, acetone, boiled distilled water, tissue paper, soil sample, analytical balance (BM 500), and an oven (Memmert UM 500). The bulk density (r_s) of the soil was determined by the following equation:

$$\rho_s = \frac{\rho_f . M_3}{M_{fd}} \tag{3}$$

where r_f is density of liquid (g/cm^3), M_s is solid mass of oven dry soil (g), M_{fd} is mass of liquid displaced by soil sample (g).

The volumetric weight of the soil (r_b) was determined using a ring sample. The tools used consisted of a sample ring with diameter f = 7.63 cm and 4 cm high, an aluminum cup, an analytical balance (BM 500), and an oven (Memmert UM 500). The volumetric weight of soil (r_b) was calculated using the following equation:

$$\rho_b = \frac{M_s}{V_t} \tag{4}$$

where M_s is dry weight of the soil mass in the sample ring (g), and V_t is volume of the sample ring.

Soil porosity was determined by the following formula:

$$x_4 = \left(1 - \frac{\rho_b}{\rho_s}\right) \tag{5}$$

3. Soil permeability (y)

Soil permeability measurements were carried out in the laboratory. The tools used were sample rings with f = 7.63 cm and 4 cm high, gauze cloth, reservoir box, soaking tank, graduated glass, stopwatches, and permeability measuring devices. The soil sample in the ring was covered with gauze cloth at the bottom, then immersed in a water tub with a water level of about 3 cm for more than 12 hours or until the soil appears wet (Klute & Dirksen, 2018). Next, the top of the ring was connected to the empty ring and tied using waterproof adhesive tape. Furthermore, the soil sample was transferred to the measurement tool, then the water was flowed into the tool and is maintained so that the water level above the soil sample is constant. The volume of water that comes out of the soil sample is measured for a certain period of time. Permeability (y) was calculated using the following formula:

$$y = \frac{Q \times L}{A \times H \times t} \quad (6)$$

where y is soil permeability (cm/h), Q is volume of water passing through the soil sample (cm^3), L is thickness of soil sample (cm), A is surface area of the soil sample, H is height of the water level above the ground (cm), and t is measurement time (h).

2.5. Data Analysis

Data on the relationship between the fraction or percentage of soil constituent and soil permeability and the relationship between the fraction or percentage of soil constituent and porosity were analyzed using SPSS application with a level of a = 5% which commonly used in agricultural research. First, the multiple linear regression analysis used all 3 input variables consisting of percentage of sand (x_1), percentage of silt (x_2), and percentage of clay (x_3) with the dependent variable soil permeability (y). The relationship between porosity and soil permeability was analyzed by developing a power equation using excel, with the independent variable soil porosity (x_4) and the dependent variable soil permeability (y).

To determine the level of accuracy of the model, the Relative Root Mean Square Error (RRMSE) was calculated of the permeability value predicted by the model with the measurement results. The RRMSE value was used to measure how far the prediction is from the observed value. The smaller the RRMSE value, it can be said that the model is more accurate.

3. RESULTS AND DISCUSSION

The soil samples used in this study had different soil textures, namely loam: corn fields in Tanjung Bintang; silt clay loam: rubber plantation LTPD; clay loam: cassava field Kotabaru and chili field Gisting; and clayey: cocoa plantations (BPP) and corn fields Polinela. The amount of data used in this study consisted of 28 data for model building and 14 data for model validation. The data consists of the percentage of sand fraction (x_1) ranging from 3.49% to 53.77%; the percentage of dust fraction (x_2) ranged from 15.83% to 45.39%; and the clay fraction (x_3) ranged from 17.90% to 75.18%. Soil porosity (x_4) ranged from 39.19% – 62.65% with soil permeability (y) ranging from 15.39 cm/hour (fast category) to 27 cm/hour (very fast category). The statistical description of the data used is presented in Table 1.

Table 1. Values of permeability (y) and fraction of sand (x_1), silt (x_2), clay (x_3) and porosity (x_4)

Parameter	Maximum	Minimum	Mean
y (cm/h)	27.92	15.39	20.65
x_1 (%)	53.77	3.49	21.96
x_2 (%)	45.39	15.83	33.67
x_3 (%)	75.18	17.90	44.36
x_4 (%)	62.65	39.19	49.37

3.1. Empirical Model of Soil Texture and Permeability (y_1)

The results of the analysis using SPSS software on the relationship between texture and soil permeability is expressed in the form of multiple linear regression equations with the independent variables silt (x_2) and clay (x_3) and the dependent variable permeability (y_1). The sand fraction (x_3) was excluded from the analysis because the sand percentage data (x_3) was not significant on the soil permeability (Table 2).

Table 2. Excluded variable

	Beta In	t	Sig.
Sand (x_1)	-837.883	1.863	0.075*

* a variable is significant if *Sig.* value is < 0.05

The results of multiple linear regression analysis (Table 3) state that the percentage of silt (x_2) and the percentage of clay (x_3) has a correlation value of 0.954 with soil permeability (y). Based on the correlation category table (Table 4), the correlation value between the percentage of silt (x_2) and clay (x_3) with soil permeability is in the range of 0.8 – 1, which indicates that the percentage of silt (x_2) and clay (x_3) has a very strong correlation with soil permeability.

Table 3. Summary model of multiple linear regression analysis of the relationship between the percentage of silt (x_2) and clay (x_3) with soil permeability (y)

Model Summary	
R	0.954
R Square	0.910
Adjusted R Square	0.903
Standard Error	1.201

Table 4. Correlation category based on R^2 value

R2 values	Correlation category
0.00 – 0.199	Very low
0.20 – 0.399	Low
0.40 – 0 599	Medium
0.60 – 0 799	Strong
0.80 – 1.00	Very strong

Source: (Sugiyono, 2006)

The value of the coefficient of determination expressed by adjusted *R* square is 0.903, indicating that the percentage of silt (x_2) and clay (x_3) can explain the permeability of 90.3%, while the rest is influenced by other factors outside the factors studied.

The results of the ANOVA test shows that overall, the variables of silt (x_2) and clay (x_3) had a significant effect on soil permeability, with a significance value of <5%. The results of the ANOVA test can be seen in Table 5.

The individual effect of each variable on permeability states that the variable percentage of silt (x_2) and clay (x_3) has a significant effect on permeability, with a sig. < 0.05. This can be seen in the multiple linear regression coefficient table presented in Table 6.

Table 5. Result of ANOVA test on the relationship between percentage of silt (x_2) and clay (x_3) on soil permeability (y)

	Df	SS	MS	F	Sig.
Regression	2	364.621	182.311	126.295	0.000*
Residual	25	36.088	1.444		
Total	27	400.709			

* significant if *Sig.* value is < 0.05

Table 6. Multiple Linear Regression coefficient table

	Un-Standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Error	Beta		
Constant	36.796	1.615		22.778	0.000
Silt (x_2)	-16.022	1.188	-0.374	-5.026	0.000
Clay (x_3)	- 23.938	1.581	-1.125	- 15.138	0.000

* significant if *Sig.* value is < 0.05

Based on the values of the coefficients in Table 5, an empirical model is made in the form of a regression equation to predict the permeability of the soil with the independent variable percentage of silt (x_2) and percentage of clay (x_3), which is expressed in equation (7):

$$y_1 = f(x_2, x_3) = 36.796 - 16.022x_2 - 23.938x_3 \tag{7}$$

The empirical model in equation (7) shows that the percentage of silt (x_2) and clay (x_3) has a negative effect on soil permeability values. This implied that decreasing the percentage of silt and clay will increase the permeability of the soil. This empirical model applies to soils with a percentage range of silt fraction (x_2) between 15.83% and 45.39% and clay fraction (x_3) between 17.90% and 75.18%.

To find out the accuracy of the model equation $y_1=36.796-16.022x_2-23.938x_3$, model validation was carried out by comparing observation data and predictive data. Comparison of observational data (y) and predictive data (y_1) is presented in graphical form on the relationship between the permeability values of the observed results and the predicted results, and the determinant value (R^2) and its RRMSE are calculated. The graph of the relationship between the observed permeability value and the predicted results of the equation $y_1=f(x_2,x_3)$ can be seen in Figure 2.

Figure 2 shows that the empirical model obtained can be used well to predict soil permeability with an R^2 of 0.925. The predicted value has a very strong correlation with the observed value because R^2 value in the range of 0.80 – 1.00 (Sugiyono, 2006). In this case, the permeability value predicted from the model is close to the measurement value, which is indicated by the RRMSE value of 5.461%. The validation results are classified as very good (excellent) because the RRMSE value of less than 10% (Despotovic *et al*., 2016; Haryanto *et al*., 2020; Li *et al*., 2013).

In Figure 2 it can be seen that within the tolerance limit of 10% for the difference in the predicted and observed permeability values, only 2 of the 14 test data are outside the tolerance limit. This mean that 86% data of the predicted value are within acceptable within ± 10% of the measured values. This is a strong indication that the empirical model obtained is suitable for predicting soil permeability values.

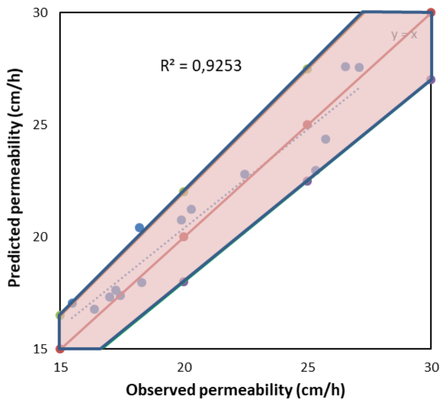

Figure 2. The graph of predicted vs. measured soil permeability (the shaded area is ± 10% from line of $y_1 = y$, that is predicted values matched perfectly the measured values)

3.2. Empirical Model of Porosity (x_4) with Soil Permeability (y_2)

Porosity is one of the physical characteristics of the soil that affects the permeability of the soil. According to Mulyono *et al.* (2019), soil permeability increases when (a) the aggregation of soil grains into crumbs, (b) there are passages or holes due to decomposed plant root, (c) the presence of organic matter, and (d) high soil porosity. The observation results show that soil permeability tends to increase with increasing porosity, as presented in the graph of the relationship between porosity and soil permeability in Figure 3.

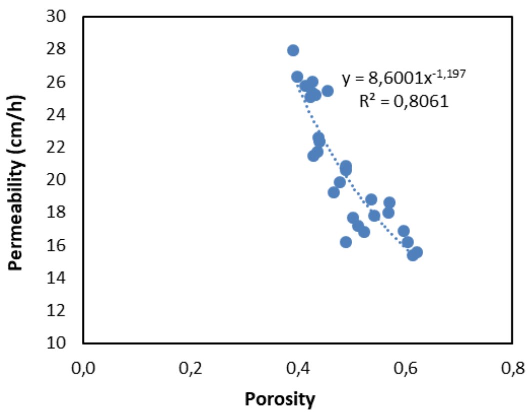

Figure 3. Relation of soil porosity with soil permeability and an ordinary power function.

Figure 3 shows that the relationship between soil permeability (y^2) and soil porosity (x_4) can be represented by the power function. The Excel application can display this relation automatically in the form $y_2 = 8.6001(x_4)^{-1.197}$ with a value of R^2 = 0.806 (very strong).

This relationship can be improved by developing a model to predict permeability using the power function in the Excel application with the general form: $y = A + B (x - C)^N$. Constants A, B, C, and N are obtained by trial and error method to get the highest R^2 value. The results of the analysis of the relationship between porosity and permeability can be expressed in the form of a power function equation with a value of A = 12, B = 0.65, C = 0.06, and N = −2.92 with a value of R^2 = 0,8417. The empirical model of the relationship between porosity (x_4) and permeability (y_2) is presented in the graph of Figure 4, and is expressed in the form of an equation:

$$y_2 = f(x_4) = 12 + 0.65(x_4 - 0.06)^{-2.92} \quad (8)$$

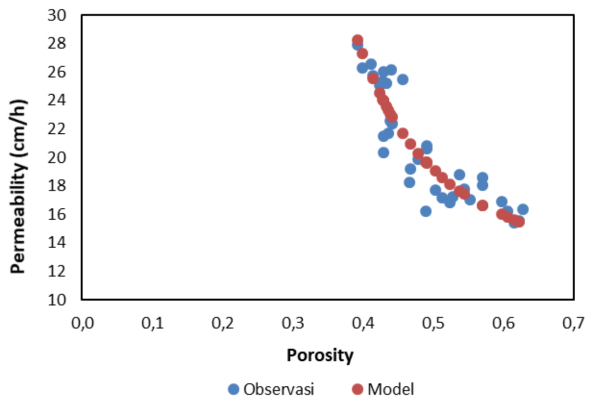

Figure 4. Relation of porosity and permeability (red dots are permeability values predited using y = A + B (x – C)^N

To determine the accuracy of the empirical model $y_2=12+0.65(x_4-0.06)^{-2.92}$, model validation was carried out by comparing observed data and predictive data. Comparison of observational data (y) and predictive data (y_2) is presented in the form of a graphical relationship between the permeability values of the observed results and the predicted results, and the determinant value (R^2) and its RRMSE are calculated. The graph of the relationship between the observed permeability value and the predicted results of the equation $y_2=f(x_4)$ can be seen in Figure 5.

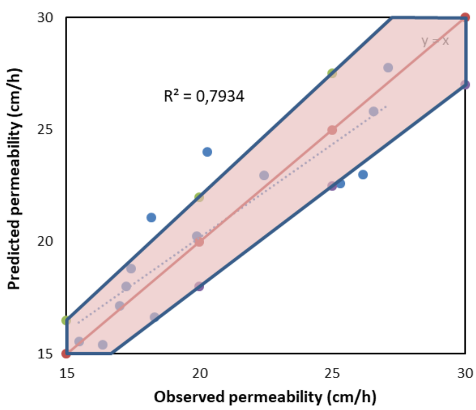

Figure 5. Graph of predicted vs. observed soil permeability (the shaded area is ± 10% from line of $y_1 = y$, that is predicted values matched perfectly the measured values)

Figure 5 shows that the value of determination coefficient R^2 is 0.7934. This shows that the permeability value predicted using the equation $y_2 = f(x_4)$ has a strong correlation with the observed value. The range of R^2 values is between 0.60 and 0.79 indicating that the predicted value and the observed value have a strong correlation (Sugiyono, 2007). The RRMSE value of 8.866% indicates that the predicted permeability value is close to the measurement value because the RRMSE is less than 10% (Despotovic *et al*., 2016; Haryanto *et al*., 2020; Li *et al*., 2013).

In Figure 3 it can be seen that within the tolerance limit of ±10% the difference of predicted and observed permeability values of the 14 data sets, 4 among the data are outside the tolerance limit. This is an indication that the empirical model is suitable for predicting soil permeability values.

The validation results of the two empirical models show that the permeability equation as a function of the percentage of silt and clay *($y_1=f(x_2,x_3)$)* can predict soil permeability better than the permeability equation as a function of porosity *($y_2=f(x_4)$)*. This is indicated by the R^2 vlaue of y_1 which is greater than that of y_2 and the RRMSE value of y_1 which is smaller than that of y_2.

4. CONCLUSION

The soil used in the study has a range of sand percentage values between 3.49% - 53.77%; dust between 15.83% - 45.39%; clay between 17.9 – 75 18%; soil porosity between 41.07% – 61.31% and permeability between 15.39 cm/hour – 27.92 cm/h. This study produced 2 empirical models of soil permeability estimation equations, namely (1) empirical equation of soil permeability as a function of the percentage of silt (x_2) and clay (x_3), and (2) empirical equation of permeability as a function of porosity (x_4). Permeability as a function of the percentage of silt (x_2) and clay (x_3) is expressed by the equation $y_1 = 36.796—16.022x_2 -23.938x_3$ with a value of R^2 = 0.925 and RRMSE = 5.461%. Permeability as a function of porosity (x_4) is expressed by the equation $y_2 = 12 + 0.65 (x_4 - 0.06)^{-2.92}$ with R^2 = 0.795 and RRMSE = 8.866%.

Based on R^2 and RRMSE values, the empirical model of permeability as a function of the percentage of silt and clay: $y_1 = f(x_2, x_3)$ can predict better than the empirical model of permeability as a function of porosity: $y_2 = f(x_4)$.

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