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Mathematical modelling of thin layer solar drying of whole okra (*Abelmoschus esculentus* (L.) Moench) pods

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Abstract

A flat plate type natural convective solar dryer was designed and constructed for conducting thin layer drying experiments of whole okra pods. Determination of the air-drying characteristics of thin layer solar drying process of whole okra pods and simulation of thin layer solar drying process of whole okra pods by two drying models, namely; Newton (Lewis) model and Page model were investigated. The drying process of whole okra pods was carried out during three successive days interrupted by two night periods. The drying air is heated by the solar dryer satisfactory and the maximum attained difference between air temperature inside the solar collector and the ambient temperatures was 41.9°C. The dramatic moisture reduction of okra pods took place during the first day of the drying process. Okra pods were dried from a decimal initial moisture content of about 5.51 d.b. (84.64% w.b.) to a decimal final moisture content of about 0.16 d.b. (13.61% w.b.). The drying process occurs in falling rate period and moisture diffusion was the dominant physical mechanism governing moisture movement within the okra pods. The probability of being wrong if the null hypothesis is rejected for Newton (Lewis) model was 0.88, while for Page model it was 1.0 ($P < 0.05$). The two tested drying models predicted whole okra pods drying process adequately but Page predictions were more accurate.

Introduction

Okra (*Abelmoschus esculentus* (L.) Moench) is an economically important vegetable crop grown in tropical and sub-tropical parts of the world. This crop is suitable for cultivation as a garden crop as well as on large commercial farms (Tripathi *et al.*, 2011). The largest ten producers are India, Nigeria, Sudan (former), Iraq, Côte d'Ivoire, Pakistan, Egypt, Ghana, Saudi Arabia and Cameron. World okra production was 6,876,584 MT, while Sudan (former) okra production was 256,000 MT (FAOSTAT, 2010). Okra is known by many local names in different parts of the world. It is called lady's finger in England, gumbo in the United States of America, guino-gombo in Spanish, guibeiro in Portuguese, bhindi in India, bamya in some Arabic countries and Turkey (Tripathi *et al*., 2011). Okra probably originates in East Africa, quite possible in Ethiopia (Doymaz, 2005). It is a tender plant and grown nearly in all parts of the Sudan (former). It is consumed by almost all the Sudanese either as green immature pods (fried or cooked or in soup or stews) or sun dried and ground into a powdery form locally known as "wieka" which is used as an ingredient in the preparation of a favourable Sudanese soup (Osman, 2005). Okra can be consumed as a fresh vegetable, a cooked vegetable or as an additive for soups, salads and stews. It provides some amount of vitamins, dietary fibre, energy and minerals (Doymaz, 2005). It is commonly processed into soup and stew but in addition can be used in processing of other food items such as candies and in salad dressing and cheese spreads (Owolarafe and Shotonde, 2004). Drying is one of the oldest methods of food preservation and it represents a very important aspect of food processing. The main aim of drying products is to allow longer periods of storage, minimise packaging requirements and reduce shipping weights. Sun drying is the most common method used to preserve agricultural products in many parts of the world. However, it has some problems related to the contamination with dust, soil, sand particles and insects and being weather dependent. Also, the required drying time can be quite long. Therefore, the drying process should be undertaken in closed equipment to improve the quality of the final product (Domyaz, 2006). Okra is traditionally preserved by drying on various surfaces such as the ground, racks, trays and concrete floors. Therefore, an effective means of overcoming the problems of sun drying is

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to dry the okra and other vegetables with solar and hot-air dryers (Doymaz, 2005). Solar drying refers to the methods of use of sun energy for drying but excludes open-air sun drying. The justification for the use of solar dryers is that: they may be more effective than sun drying and have lower operating costs than mechanized dryers. Solar dryers can be constructed from locally available materials at a relatively low capital cost and there are no fuel costs. Thus, they can be useful in areas where fuel or electricity are expensive, land for sun drying is in short supply or expensive, sun shine is plentiful but the air humidity is high. Moreover, they may be useful as a means of heating air for artificial dryers to reduce fuel costs. Sudan (former) lies within the tropics between latitudes 22°N and 3°N. Like many other countries of the tropics, Sudan (former) is blessed with plentiful sun shine all the year round, where the duration of the sun shine ranges from 10-12 hours daily with average solar radiation of more than 20 MJ m^{-2} day^{-1} (Akoy, 2000). Solar dryers must be properly designed in order to meet particular drying requirements of agricultural products and give satisfactory performance concerning energy requirements. The prediction of drying rate of the specific crops under various conditions is of importance for the design of the drying systems. Full-scale experimentation for different products and systems configurations is sometimes costly and not possible. The use of a simulation model is a valuable tool for prediction of performance of solar drying systems (Sacilik *et al.*, 2006). Many investigators have carried out mathematical modelling and experimental studies on the thin layer drying of various vegetables and fruits. For example, potato slices (Aghbashlo *et al.*, 2009), onion slices (Arslan and Özcan, 2010), coroba slices (Corzo *et al.*, 2008), okra (Doymaz, 2005), sweet cherry (Doymaz and Ismail, 2011), mango slices (Goyal *et al.*, 2006), pistachios (Kouchakzadeh and Shafeei, 2010) and carrots (Zielinska and Markowski, 2010). However, there is little information about thin layer solar drying process of okra in the literature. Therefore, the objectives of this study were: (i) determination of the air-drying characteristics of thin layer solar drying process of whole okra pods and (ii) simulation of thin layer solar drying process of whole okra pods by testing two drying models.

Materials and Methods

Experimental dryer

A flat plate type natural convective solar dryer was designed and constructed from local materials at the Workshop of the Department of Agricultural Engineering, Faculty of Agriculture, University of Khartoum, Sudan (former). The constructed dryer consisted of a drying chamber and a solar collector combined in one unit. The solar collector comprises a rectangular prism frame (1050.8 mm long, 1050.8 mm wide and 300.8 mm high) which was made of steel square tubing (25.4 mm x 25.4 mm) with a wall thickness of 1.25 mm. Five masonite sheets 3 mm thick were externally fixed by rivets onto five sides of the frame except the upper one. Another five steel sheets 2 mm thick were internally welded onto five sides of the frame except the upper one. Glass wool was inserted in gap between the masonite and the steel sheets and was used as an insulator. The metal sheets were painted in black in order to absorb more solar radiation. One square panel of 4 mm thick transparent glass (1025.4 mm x 1025.4 mm) was glued to the upper side of the frame with silicon rubber sealant. The drying chamber consisted of two cylinders made of steel sheets 2 mm thick and were fitted coaxially. The inner cylinder is removable with a perforated base and was used for holding whole okra sample during drying process. The solar collector was welded to the drying chamber. The solar dryer was placed on a trapezoidal support (300 mm high at the front and 570 mm high at the back) which was made of angle irons (38.1 x 38.1 mm). The trapezoidal shape of the angle iron support was intended to incline the glass cover of the solar collector at an angle of 15° due South, which is the inclination angle of the latitude of the experimental site. The constructed dryer was used in conducting the thin layer drying experiments of whole okra pods. A schematic view of the experimental solar dryer setup is shown in Figure 1.

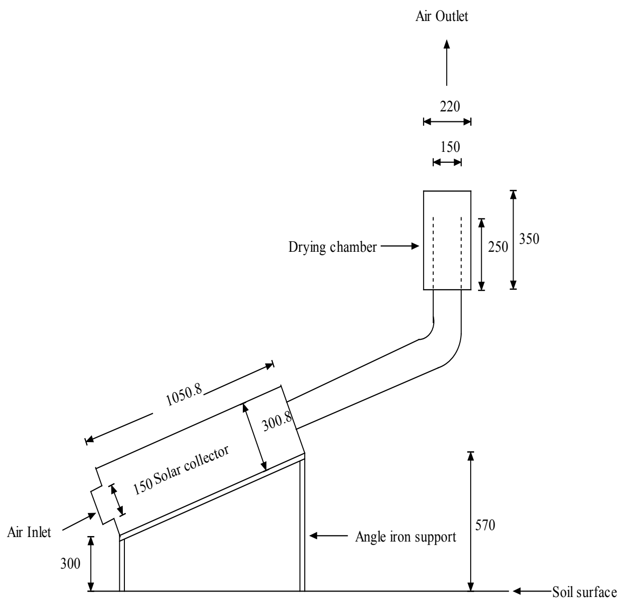

Figure 1. Schematic view of the experimental solar dryer setup (all dimensions in mm)

Experimental procedure

Fresh whole okra pods were purchased from the local market of Khartoum North, Sudan (former) and kept in a refrigerator at 4°C before commencing the study experiments. The initial moisture content of okra was determined using AOAC (1965) method and was found to be 84.64% (w.b.). In this method triplicate representative samples of 5 g each of whole okra pods were taken from the okra lot and were cut into slices of approximately 5 ± 0.1 mm thickness by using a sharp stainless steel knife. The sliced okra samples were put into three empty metal moisture cans of known weights. The moisture cans were then put inside a hot air oven set at a temperature of 105°C for 24 hours. After the 24 h drying time the moisture cans were removed from the oven and placed into a desiccator until they got cold. The loss in weight of okra samples was recorded using a digital balance of ± 0.01 g accuracy (YSS-620, Yamato Scale Co, Ltd, Akashi, Japan) and expressed as their initial moisture content values on wet basis and dry basis as calculated by equations 1 and 2, respectively.

$$M_{0wb} = \frac{W_1 - W_2}{W_0} \quad (1)$$

$$M_{0db} = \frac{W_1 - W_2}{W_3} \quad (2)$$

where,
M_{0wb} = initial moisture content of okra sample on wet basis, decimal
W_1 = weight of undried okra sample + weight of metal moisture can, g
W_2 = weight of dried okra sample + weight of metal moisture can, g
W_0 = initial weight of undried okra sample, g
M_{0db} = initial moisture content of okra sample on dry basis, decimal
W_3 = final weight of dried okra sample, g

A sample of 12.09 g of whole okra pods was uniformly spread in a thin layer on the perforated base of the inner cylinder of the drying chamber. The initial wet weight of the whole okra sample was recorded using the digital balance. Daily the thin layer solar drying experiments were started at 9:00 and at terminated at 18:00. The losses in weight of drying okra sample were recorded at intervals of one hour due to the slow change in the moisture content of the okra pods and each weighing took about 30 s in order to avoid any moisture exchange between the okra pods and the surrounding atmosphere. The recorded losses in weight of drying okra sample were then converted into corresponding moisture contents on wet basis and dry basis by using equations 3 and 4, respectively as reported by (Ekechukwu, 1999).

$$M_{twb} = 1 - \left[\frac{(1 - M_{0wb}) * W_0}{W_t}\right] \quad (3)$$

$$M_{tdb} = \left[\frac{(M_{0db} + 1) * W_t}{W_0}\right] - 1 \quad (4)$$

where,
M_{twb} = moisture content of okra sample on wet basis at time t, decimal
W_t = weight okra sample undergoing drying at time t, g
M_{tdb} = moisture content of okra sample on dry basis at time t, decimal

At the end of each drying day the whole okra pods sample was wrapped by aluminum foil in order to prevent moisture exchange between the sample and the surrounding atmosphere. The thin layer solar drying experiments were run until constant weight of okra sample was reached and it this was achieved at the end of the first day. To make sure that the okra sample reached a constant weight, the drying experiments were extended for another two days i.e. the drying experiments took three consecutive days interrupted by two night periods. During the thin layer drying experiments air temperatures measurements were made by using copper-constantan thermocouples of ± 0.2°C accuracy connected to a data logger (2e Delta T-logger, Delta-T Device Ltd, Cambridge, UK) which was configured to record at intervals of one hour. The measurements were taken for (i) ambient, (ii) at inlet of the solar collector, (iii) inside the solar collector and (vi) at outlet of the drying chamber.

Modelling of thin layer solar drying of whole okra pods

Thin layer drying mean to dry as one layer of sample particles or slices. Thin layer drying models (moisture ratio equations) that describe the drying phenomenon of agricultural materials mainly fall into three categories, namely theoretical, semi-theoretical and empirical. The first takes into account only internal resistance to moisture transfer while the other two consider only external resistance to moisture transfer between product and air (Akpinar, 2006; McMinn, 2006). Among semi-theoretical thin layer drying models, the Newton (Lewis) model, Page model, the modified Page model, the Henderson and Pabis model, the logarithmic model, the two-term model, the two-term exponential, the diffusion approach model, the modified Henderson and Pabis model, the Verma *et al*. model and the Midilli–Kucuk model are used widely (Akpinar, 2006).

Newton model describes that the moisture transfer from the foods and agricultural materials can be seen as analogous to the flow of heat from a body immersed in cool fluid. This model assumes negligible internal resistance, which means no resistance to moisture movement from within the material to the surface of the material. By comparing this phenomenon with Newton's law of cooling, the drying rate is proportional to the difference in moisture content between the material being dried and equilibrium moisture content at the drying air condition as:

$$MR = \exp(-kt) \quad (5)$$

where,
MR = moisture ratio, dimensionless
k = drying rate constant, h^{-1}
t = drying time, h

This model was used primarily because it is simple (Kashaninejad *et al.*, 2005). The only drawback, however, it underestimates the beginning of the drying curve and overestimates the later stages (Simal *et al.*, 2005).

Page model suggests a two constant empirical modification of the Newton model to correct for its shortcomings. This model has produced good fits to describe drying of many foods and agricultural products (Kashaninejad *et al.*, 2005). This model is expressed as:

$$MR = \exp(-kt^{n}) \quad (6)$$

where,
MR = moisture ratio, dimensionless
k = drying rate constant, h^{-1}
t = drying time, h
n = constant

The experimental drying curve of whole okra pods was fitted using Newton (Lewis) and Page model as reported by previous works (Arslan *et al.*, 2010; Arslan and Özcan, 2010; Doymaz, 2010; Jazini and Hatamipour, 2010; Kaleta and Górnicki, 2010; Xanthopoulos *et al.*, 2010; Dissa *et al.*, 2011; Meziane, 2011).

The moisture ratio (MR) in equations 5 and 6 is calculated using equation 7 as follows:

$$MR = \frac{(M_{tdb} - M_{edb})}{(M_{0db} - M_{edb})} \quad (7)$$

where,
M_{edb} = equilibrium moisture content of okra sample on dry basis, decimal

MR has been simplified to M_t/M_0 by some investigators (Wang *et al.*, 2007; Akpinar and Bicer, 2008; Madhiyanon *et al.*, 2009; Meziane, 2011) because of the continuous fluctuation of the relative humidity of the drying air during the thin layer solar drying of okra pods. The constant(s) of the two tested drying models were calculated experimentally by normalization (linearization) the equation form for each model by employing the linear regressing technique using Microsoft® Office Excel 2003 software. The normalized form of Newton (Lewis) and Page models are given by equations 8 and 9, respectively.

$$\ln(MR) = -kt \quad (8)$$

$$\ln[-\ln(MR)] = -\ln(k) + n\ln(t) \quad (9)$$

In equation 8 "k" represents the slope of the straight line, whereas "ln$k$" and "n" in equation 9 represent the intercept and slope of the straight line, respectively. The goodness of fit of the two tested drying models to the experimental data was evaluated based on criteria such as as: the two sample independent t-test and in addition to three statistical parameters namely; average model error (*AME*), average absolute difference (*AAD*) and standard error of estimate (*SEE*) or sometimes is known as root mean square of error (*RMSE*). *AME*, *AAD* and *SEE* are calculated by equations 10, 11 and 12, respectively.

$$AME = \frac{\sum_{i=1}^{n}(\exp._{i} - pred._{i})}{N} \quad (10)$$

$$AAD = \frac{\sum_{i=1}^{n}(abs(\exp._{i} - pred._{i}))}{N} \quad (11)$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(\exp._{i} - pred._{i})^2}{N}} \quad (12)$$

where,
AME = average model error expressed as moisture content on dry basis, decimal
$exp._i$ = ith observation for the experimental moisture content on dry basis, decimal
$pred._i$ = ith observation for the predicted moisture content on dry basis, decimal
N = number of observations
AAD = average absolute difference expressed as moisture content on dry basis, decimal
SEE = standard error of estimate expressed as moisture content on dry basis, decimal

Abbouda (1984) stated that an accurate model

Table 1. Two-sample independent t-test in the sample means (expressed as moisture content on dry basis, decimal) of experimental and predicted moisture contents by the two tested drying models

Model name	95% confidence interval for $\mu_1 = \mu_2$	$\mu_1 = \mu_2$ vs $\mu_1 \neq \mu_2$			
		t_0	t_t	P	df
(Lewis) model	(-1.62, 1.88)	0.15	2.11	0.88	17
Page model	(-1.79, 1.79)	-0.00	2.11	1.0	17

μ_1 = population mean of the experimental moisture content on dry basis, decimal
μ_2 = population mean of the predicted moisture content on dry basis, decimal
t_0 = calculated value of test statistic
t_t = tabulated value of the upper α/2 percentage point of the t-distribution
P = probability or percent risk of being wrong if the null hypothesis (H_o) is rejected
df = degrees of freedom

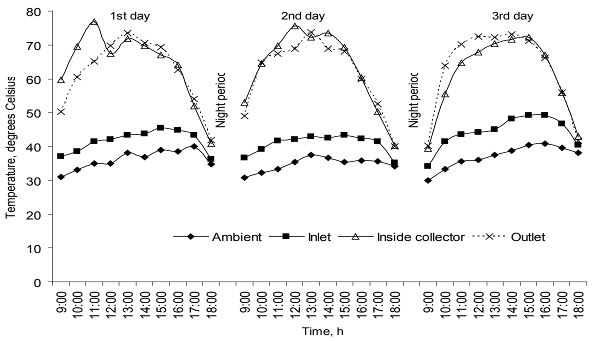

Figure 2. Air temperatures of ambient, at inlet of solar collector, inside solar collector and at outlet of solar collector during the three days of the drying process

should have an average model error (*AMA*) and an average absolute difference (*AAD*) close to zero and a small standard error of estimate (*SEE*). MINITAB statistical, Release 13.30 software was used for carrying out the statistical analysis for validation of the two drying models being tested. A computer programme using Turbo Pascal for Windows, Version 1.5 was then written for each of the two tested drying models for simulating the drying process of whole okra pods during the first day (effective drying period).

Results and Discussion

Determination of the air-drying characteristics of thin layer solar drying process of whole okra pods

Figure 2 shows air temperatures for ambient, at the inlet of the solar collector, inside the solar collector and at the outlet of the drying chamber during the three days of the drying process of okra pods. The interruptions of the lines in the figure represent two overnight periods during the drying

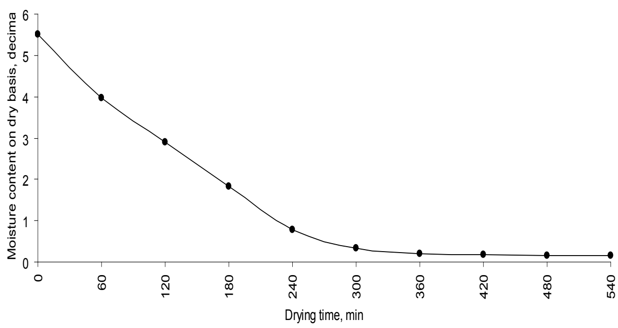

Figure 3. Drying curve of moisture content versus drying time of whole okra pods during the first day of the drying process

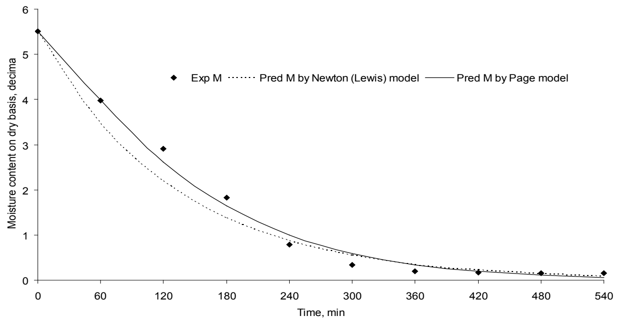

Figure 4. Experimental and predicted moisture contents of whole okra pods during the first day of the drying process

process. The four temperatures start to increase in the morning, reach the maximum at noon and then decrease towards evening. From the figure it is clear that air temperatures inside the solar collector and at the outlet of the drying chamber temperatures are close to each other, whereas the same can be said for air temperatures of the ambient and at the inlet of the solar collector. The maximum attained difference between air temperature inside the solar collector and the ambient temperatures is 41.9°C. This shows that the drying air is heated by the dryer satisfactory.

Figure 3 shows the drying curve of whole okra pods and it was obtained by plotting moisture content versus drying time for the first day of the drying process of okra pods. The data of the first day was chosen because the dramatic moisture reduction of okra pods took place in that day. Okra pods started drying from a decimal initial moisture content of about 5.51 d.b. (84.64% w.b.) to a decimal final moisture content of about 0.16 d.b. (13.61% w.b.). From the figure it is clear that the drying process occurs in falling rate period i.e. there is no constant rate drying period in the drying of okra pods. This indicates that diffusion is the most likely the dominant physical mechanism governing moisture movement within the okra pods. Similar results were obtained by Akpinar and Bicer (2008) for long green pepper, Doymaz (2005) for okra, Doymaz (2006) for mint leaves, Doymaz (2007) for tomatoes, Doymaz (2010)

Table 2. Average model error (*AMA*), average absolute difference (*AAD*) and standard error of estimate (*SEE*) between experimental and predicted moisture contents by the two tested drying modelsexpressed as moisture content on dry basis, decimal

Modelname	*AME*	*AAD*	*SEE*
(Lewis) model	0.128	0.224	0.324
Page model	-0.001	0.125	0.160

for Amasya red apples, Madhiyanon *et al.* (2009) for chopped coconut and Meziane (2011) for olive pomace. Also it is clear that at the end of the first day of the drying process an equilibrium state is attained. Similar types of observations were given by Ayoub (2006) for tomato slices, Elzaki (2008) for banana slices and Salih (2008) for guava slices.

Simulation of thin layer solar drying process of whole okra pods

Figure 4 shows the experimental (measured) and predicted moisture contents by Newton (Lewis) and Page models. Newton model tends to under predict the early stages and slightly over predict the later stages of the drying curve, while Page model gives good fit to experimental data of the drying curve. The less accurate prediction of moisture contents of okra pods given by Newton model could be attributed to the fact that, this model assumes negligible internal resistance to moisture movement from within the material to the surface of the material. This result is in an agreement with findings of Simal *et al.* (2005). Table 1 shows the two-sample t-test to see if there is any difference in the sample means (expressed as moisture content on dry basis, decimal) of the experimental and the predicted moisture contents of whole okra pods. The probability of being wrong if the null hypothesis is rejected for Newton (Lewis) model is 0.88, while for Page model it is 1.0 ($P < 0.05$). Also since the null hypothesis (H_o:μ_1=μ_2) holds true i.e. $|t_o| < t_t$ for the two tested drying models. This indicates that on the basis of the sampling in each of the methods (experimental and prediction by the two drying models) of moisture content determination, there is insufficient evidence to reject the null hypothesis. In other words on the basis of the present data there is no difference between the two methods regarding the determination of moisture content of whole okra pods. Also this confirms that the two tested drying models predict the whole okra pods drying process adequately. Table 2 shows the three statistical parameters *AME*, *AAD* and *SEE* for both Newton (Lewis) and Page drying models. With regard to Newton (Lewis) model, the *AME*, *AAD* and *SEE* are 0.128, 0.224 and 0.324, respectively expressed as moisture content on dry basis, decimal. While for Page model, these parameters are -0.001, 0.125 and 0.160, respectively. These values show that the two tested drying models predict whole okra pods drying process adequately, but Page predictions are in close agreement with experimental data. Similar findings were reported by Aghbashlo *et al.* (2009) for potato slices, Doymaz (2004) for carrots, Doymaz (2005) for okra, Sharma *et al*. (2005) for onion slices and Singh *et al.* (2008) for water chestnut.

Conclusions

The solar dryer increased the capacity the drying air in order to take more moisture from okra pods. The constructed solar dryer could be used as a simple, cheap and fast tool for drying whole okra pods in many rural parts of the Sudan (former). The drying process of whole okra pods could be accomplished safely during one day. Since no constant rate drying period in the drying of okra pods was observed, the average initial moisture content of okra pods was less than their critical moisture content. Moisture diffusion was the dominant physical mechanism governing moisture movement within the okra pods. The two tested drying models predicted whole okra pods drying process adequately but Page predictions were more accurate.

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