# Investigating the Thin Layer Drying Characteristics of Vegetable Kales in a Natural Convection Solar Cabinet Dryer, under the Climatic Conditions of Maseno, Kenya

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**Abstract The growth of fruits and vegetables is becoming an important component of the agricultural industry sector, as sale of dried fruits and vegetables assume commercial scale. However due to lack of processing considerable amount of losses (between 30% and 40%) of these seasonal products occur in many developing countries. Drying is one of the most common methods of preservation of agricultural products. It removes sufficient moisture from the food and prevents decay or spoilage. Majority farmers in developing countries use open-sun method for drying their harvest despite the existence of more efficient methods of drying. This method is time consuming and exposes the produce to destruction by birds, animals and contamination. The areas surrounding Maseno university is agriculturally rich and known for production of vegetables and fruits among other agricultural products. In the wet seasons there is significant waste due to lack of preservation facilities to prolong their shelf life and yet during dry seasons these products are short in supply. In the present work, a model of natural convection solar dryer with twin collectors was designed and tested with and without load under the climatic conditions of Maseno, Kenya for drying of Vegetable kales. Results of test under no load revealed that the humidity in the drying chamber was reduced by 31.4%, while the chamber temperature was raised by 11.5 o C at average air flow rate of 0.39 m/s. The moisture content in the kales was reduced from 84.1% to less than 10% in about 15 hours of drying for an average air flow of 0.39 m/s. The maximum thermal efficiencies obtained were 22.51 % and 25.52 % for collector 1 and 2 respectively. Quality tests performed on both solar dried and wet samples revealed more than 50 % retention of all the nutrients in the solar dried vegetable kales.**

***Keywords: indirect mode, natural flow, cabinet solar dryer, twin collectors***

Nomenclature

$T_2$: Out let temperature of collector 1
$T_3$: Ambient temperature
$T_6$: Drying chamber temperature
$T_7$: outlet temperature of collector 2
1 L: top left tray
1 R: top right tray
6 L: middle left tray
6 R: middle right tray
10 L: bottom left tray
10 R: bottom right tray
I R: incident solar radiation
R $H_c$: relative humidity of air in chamber
R $H_a$: relative humidity of ambient air
d1: day 1
d2: day 2
d3: day 3
d4: day 4
d5: day 5
d6: day 6
w. b.: wet basis

## INTRODUCTION

Drying, one of the most common methods of preservation of agricultural products in developing countries substantially reduces the weight and volume of the product thus minimizing packaging, storage and transportation costs, [1]. Although most developing countries have a huge potential of solar energy for agricultural drying applications, rural small scale farmers use traditional methods to inefficiently dry agricultural produce. [2]. These methods have the advantage that their requirement of solar and wind energy is readily available in nature and therefore require marginal capital investment, a fact that makes them the most viable option of drying agricultural products at both small and commercial scale in developing countries, [3]. Some of the disadvantages of these methods include: contamination of the product by dust, destruction by insects and micro-organisms, pecking by birds, loss of some nutrients (vitamin A), [4]. They are also labor intensive and totally dependent on weather conditions, [5] and therefore a cause of the huge post harvest losses of between 30 and 40 % currently encountered in these countries, [6]. These methods involve laying the product in the sun where the product absorbs part of the radiation falling on its surface and the remaining is reflected back depending on its color. The absorbed radiation is converted into thermal energy raising the temperature of the product causing evaporation of moisture, [3].

Drying is energy intensive due to the large value of latent heat of water evaporation and the use of solar energy in industrial and agricultural drying applications can lead to a significant saving of conventional fuels and reduction in pollution, [7]. In particular the development of appropriate solar technologies for agricultural applications in rural areas of developing countries can minimize post harvest losses and increase food supplies, [8]. A better alternative to open sun drying method is the use of solar dryers which are more efficient and results in better quality dried products. A solar dryer is an enclosed unit in which the product is protected from damage by birds, insects, micro-organisms, pilferage and unexpected rainfall, [9].

Drying is a heat and moisture transfer process between the material and air, the heat is transferred to the surface of the product through conduction and convection from the adjacent air at a temperature above the material, [3]. Solar drying is a process in which moisture is removed from a product by heat in the presence of a controlled flow of air. It involves the application of heat to the product to increases the vapor pressure of the moisture in the product above that of the surrounding air, creating thermal and pressure gradients causing the moisture both liquid and vapor to move to the surface of the product before the water vapor is transferred to the surrounding air by evaporation, [10]. As air at relatively lower humidity than the moisture content in the material is passed through the material, the air absorbs moisture from the material and its absolute and relative humidity increases. The efficiency of a solar dryer is affected by relative humidity in the air, the moisture content of the product to be dried, its quantity and thickness, [11]. The solar radiation intensity incident on the material varies with seasons, time of the day and length of exposure, ambient air temperature and wind speed.

The growth of fruits and vegetables is becoming an important component of the agricultural industry sector, as sale of dried fruits and vegetables assume commercial scale. However due to lack of processing, considerable amount of losses (between 30% and 40%) of seasonal fruits occur in many developing countries. [12]. Drying reduces the moisture content in these products to safe levels after harvest to prevent growth of moulds and bacterial action and allow storage over an extended period. The area around Maseno University is agriculturally rich and known for production of vegetables and fruits among other agricultural products. In the wet seasons there is significant waste due to lack of preservation facilities to prolong their shelf life and yet during dry seasons these products are short in supply. In the present work a model of indirect natural convection cabinet solar dryer was designed and tested for thin layer drying of vegetable kales under the climatic conditions of Maseno, Kenya.

## METHODOLOGY

*Description of the solar dryer*

The indirect mode solar dryer was designed to dry vegetable products under the climatic conditions of Maseno, Kenya. Its main components were drying cabinet and two solar collectors. The materials used in the construction include: well seasoned cedar wooden bars, G.I. sheets, transparent glass and polythene sheets, nails, black paint, wire mesh, Aluminum gauze, PVC waste pipes, foam sheets, glass glazing of 5 mm thickness and a 32 cm tall chimney of 15cm diameter. The solar collector system consists of two collectors each with glazing area of 2.5 m$^2$ made of wooden frames covered with glass and connected to the drying chamber via air ducts made of plastic waste pipes. The roof and sides of the drying chamber were covered with G.I sheets internally insulated with foam material covered polystyrene. The drying chamber consists of 20 trays each measuring 1.0 x 1.0 x 0.2 m, spaced 20 cm apart. The trays were of Aluminum screens on wooden frames and a 40 cm tall chimney with an inner diameter of 15 cm.

*Design Parameters Of The Solar Dryer*

The design parameters were decided based on the amount of moisture to be removed and the required air flow rate. Accordingly the length and width of chamber, size of the flat plate collectors, height and diameter of the chimney were calculated. The drying chamber was provided with a door 1.6 x 0.75m to facilitate loading and loading of the dryer.

1. The collector tilt $\gamma$ for maximum incident solar radiation normally taken as the latitude of the location, 0 $^o$ for Maseno, but in this case to allow rain off a value of $\gamma = 10^o$ was used.

2. The ratio of length to width of the air heater was taken as 1.5 and the length of the drying chamber $L_s$ is then given by
$$L_s = \frac{A_{dc}}{w} \quad (1)$$
where $A_{dc}$ and $w$ are the area and width of the collector respectively.

3. The aggregate thin drying layer thickness $h_L \leq 200mm$ was used

4. The expected mean temperature difference of heated air at the collector outlet and the ambient value is given by
$$\Delta T = 2\beta(T_b - T_c)\frac{I_t}{I_o} \quad (2)$$
where $\beta$ is a dimensionless parameter that ranges between 0.14 and 0.25 $I_t$ the intensity of radiation incident on the plane of the collector, $I_o$ the maximum intensity of the source of radiation/ solar constant value

(1367 W/m$^2$) , $T_b$ the boiling temperature of water, $T_c$ the critical temperature of water. The values were assigned as follows:

$\beta = 0.20$, $T_b - T_c = 100^oC$, $I_t = 500W/m^2$ giving a value $\Delta T = 14.6^oC$.

5. The quantity of moisture to be removed $m_w$ was obtained according to the relation

$$m_w = w_w \frac{m_i - m_f}{1 - m_f} \tag{3}$$

where $m_i$ initial moisture content, $m_f$ is final moisture content, $w_w$ is initial product mass, from literature the values were assigned as follows: $m_i = 0.73$, $m_f = 0.15$, $w_w = 50kg$, from which $m_w = 34.12kg$ is obtained.

6. The latent heat of evaporation is estimated using the equation

$$L_t = R_g T_c T_b In\left(\frac{P_c}{10^5}\right)\frac{(T_c - T_{pt})^{0.38}}{(T_c - T_b)^{1.38}} \tag{4}$$

where $R_g$ gas constant of water vapor, $P_c$ critical pressure of water, $T_{pt}$ temperature of product and given by $T_{pt} = 0.25\{3T_o + T_a\} = 312.6K$, $R_g = 287.1$ J/kg K

7. The total volume of air needed to remove the moisture was then obtained using the relation

$$V_A = \frac{m_w L_t R_a T_a}{C_{pa} P_a (T_o - T_f)} \tag{5}$$

where $R_a$ is specific gas constant $P_a$ the partial pressure of dry air in the atmosphere $C_{pa}$ the specific heat capacity of air at constant pressure $T_f = T_a + 0.25\Delta T$ the temperature of air leaving the drying chamber $T_o$ the ambient temperature $L_t$ the latent heat of vaporization of water. The values were assigned as follows: $R_a = 287J/kgK$, $T_a = 298K$ $C_{pa} = 1005J/kgK$, $T_f = 302.65K$, $P_a = 101325N/m^2$

8. The expected volume air flow rate was then obtained using the relation

$$\dot{v} = \frac{V_A}{t} \tag{6}$$

where $t$ is total time needed to dry a given sample of the product.

9. The chimney length was taken to be $1/15$ of the collector length ($4.8m$), a value of 0.32 m.

10. Thermal efficiency of the solar collector was obtained according to the equation

$$\eta_c = \frac{mC_{pa}(T_o - T_i)}{A_c I} \times 100 \tag{7}$$

where $m$ is air mass flow rate, $C$ specific heat capacity of air, $T_i$ collector inlet air temperature, $T_o$ outlet air temperature, $I$ incident solar radiation and $A_c$ the collector area.

11. The system efficiency for the solar dryer was calculated according to the equation

$$\eta_p = \frac{WL}{IA_c + P_f} \tag{8}$$

where $W$ is weight of water evaporated from the product, $L$ latent heat of vaporization of water , $P_f$ power used to drive the fan

12. The effective moisture diffusivity for agricultural products is given by

$$k = \frac{\pi^2 D_{ef}}{r^2} \tag{9}$$

where $k$ is the drying rate constant, $r$ is the characteristic thickness.

## EXPERIMENTAL PROCEDURES

### FULL LOAD TESTS UNDER NATURAL FLOW

Tests were done on the indirect mode natural flow solar dryer shown in figure 1, under no load conditions between 9:00 hrs and 16:00 hrs in the month of April and May 2014, to determine the temperature profile, relative humidity and solar radiation at different locations and moisture ratio profile of kales in the solar dryer. During the experimental drying tests, temperatures readings were taken for the ambient air and of air at various locations in the drying system (collectors and inside the drying chamber) using type J and K thermocouples connected to a Fluke 2286 data logging system at regular intervals of 10 minutes between 0900 hrs and 1600 hrs local time. The intensity of the incident solar radiation incident on the surface of the collectors was measured at one minute intervals using a portable solarimeter placed horizontally on one of the surfaces of the collectors. The relative humidity of air outside and inside the drying chamber was measured using a Psychrometer at one-hour intervals. The air flow velocity and volume flow rates were measured at the collector outlets and chimney at one-hour intervals using an anemometer model 8360. The dryer was loaded with 10 kg Kales with initial moisture content 84.41 % w. b. laid in thin layers onto each tray. The initial mass of kales loaded on the six control samples were recorded thereafter these samples were removed from the dryer and their weight measured at the at two-hourly intervals using an electronic balance. The mass of the kales during the drying hours was recorded up to the stage when no significant weight loss occurred after three consecutive weighing, at which point drying was stopped. Weight measurements were also taken from open sun-dried control samples up to the same moisture content.

Figure 1: Pictorial view of the indirect cabinet solar dryer designed at the Department of Physics and Materials Science, Maseno University, Kenya.

## *RESULTS AND DISCUSSION*

The results of tests under no load for the natural convection solar dryer presented in figures 2 - 5, reveal that the humidity of air in the chamber has a decreasing trend with increasing solar radiation. The maximum and minimum relative humidity of air in the chamber were 77.1% at 9:00 hrs and 44.3% at 16:00 hrs respectively against maximum and minimum relative humidity values of the ambient air of 75.7% at 10:00 hrs and 46.9% at 15:00 hrs respectively, a reduction of 31.4% in relative humidity in the drying chamber below the maximum ambient value, (figure 3). The maximum and minimum chamber temperatures were 38.8 $^{o}$C at 1600 hrs and 33.7 $^{o}$C at 9:00 hrs respectively against corresponding ambient maximum and minimum values of 31.6$^{o}$ C at 15:00 hrs and 27.3 $^{o}$C at 9:00 hrs respectively, (figure 5). Thus it was observed that the temperature of air in the drying chamber was increased by

11.5 $^{o}$C above the ambient value at average air flow rate of 0.39 m/s. The observed maximum and minimum solar radiation during the selected days were 1212 W/m$^2$ and 61 W/m$^2$ respectively (figure 4), while the maximum and minimum values of humidity in the ambient air during the month of April 2014 were 95.4% and 29.6% respectively, (figure 3).

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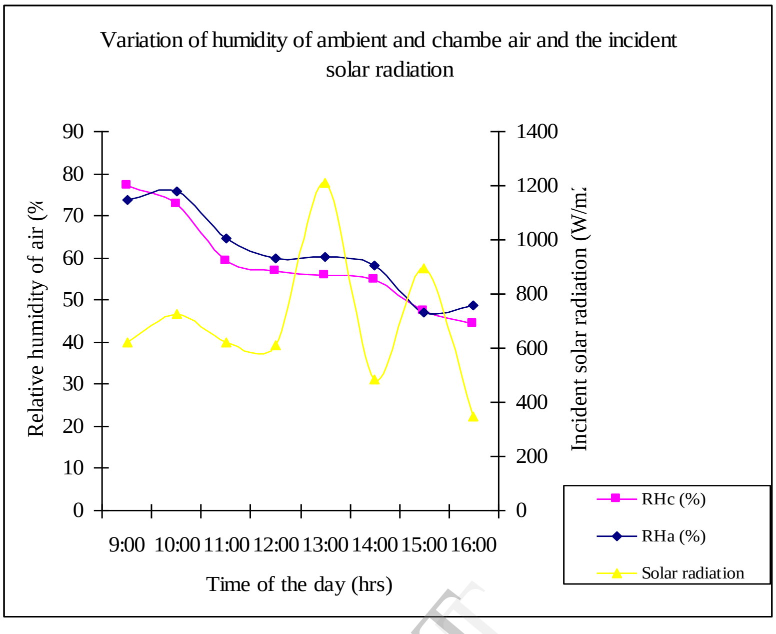


Figure 2: shows variation of relative humidity of ambient air and drying chamber with time under no load.



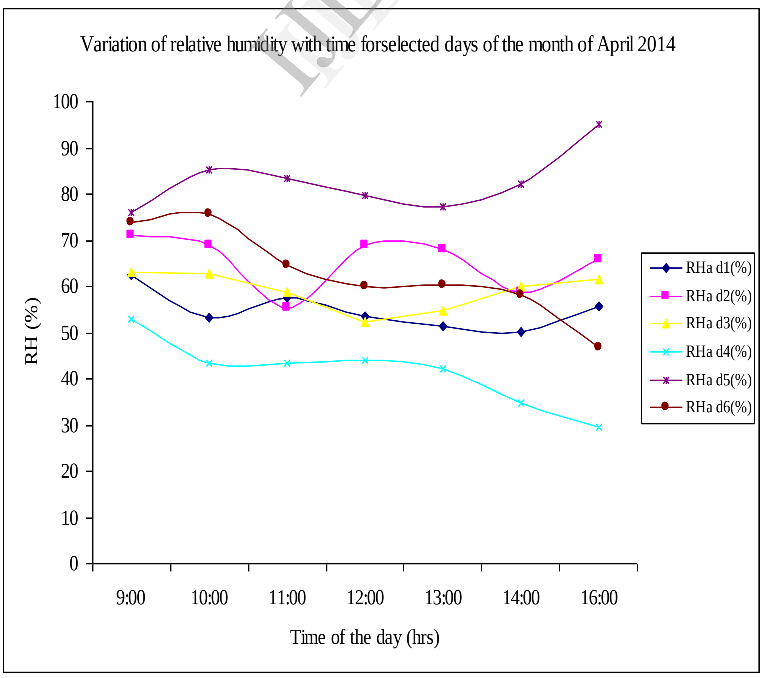


Figure 3: Variation of relative humidity of ambient air for selected days of April 2014

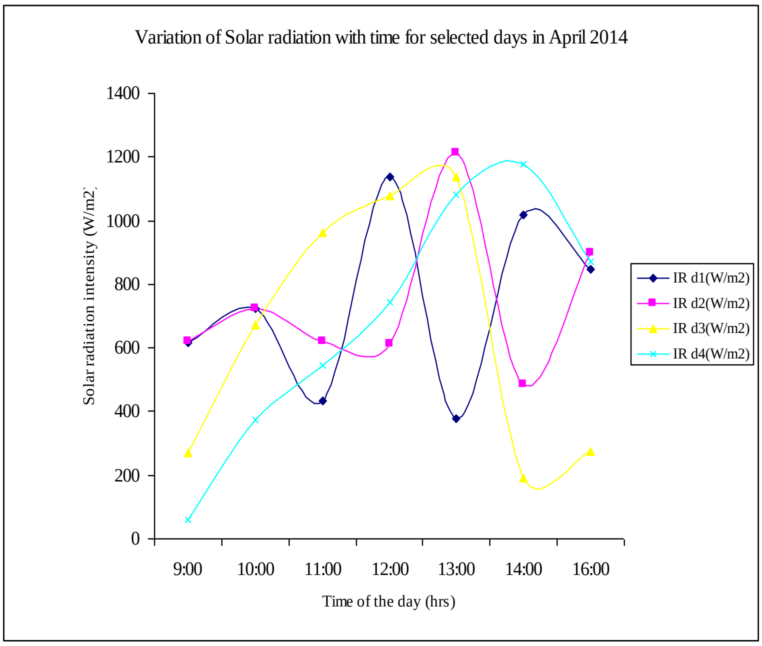


Figure 4: shows variation of solar radiation for selected days of April 2014

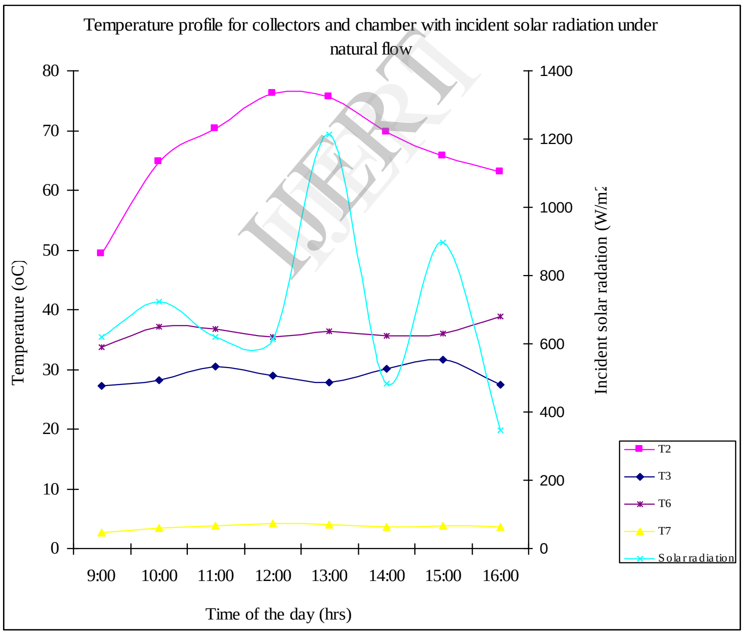


Figure 5: shows temperature profiles of the different locations in the dryer system with time under natural flow with no load.

*FULL LOAD TESTS*

The results tests on the natural convection solar dryer under full load, revealed that the maximum and minimum chamber temperatures were 36.8 °C at 1:00 hrs and 28.3 °C at 9:00 hrs respectively against corresponding ambient maximum and minimum values of 31.5 °C at 1:00 hrs and 22.4 °C at 9:00 hrs for the days of drying in April 2014. It was also observed that the maximum solar radiation for the first and second drying days in were 1080 W/m$^2$ and 1016 W/m$^2$ at 1:03 hrs while the minimum solar radiation values for the first and second days were 30 W/m$^2$ at 16:00 hrs and 290 W/m$^2$ at 10:00 hrs respectively, (figure 4).

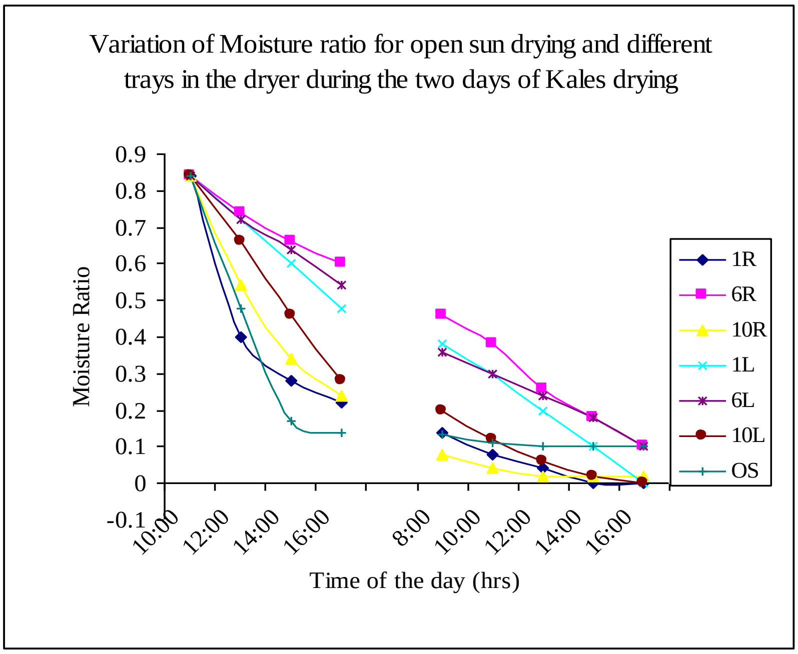


Figure 6: Variation of moisture in the Kales with time for the top, middle and bottom trays.

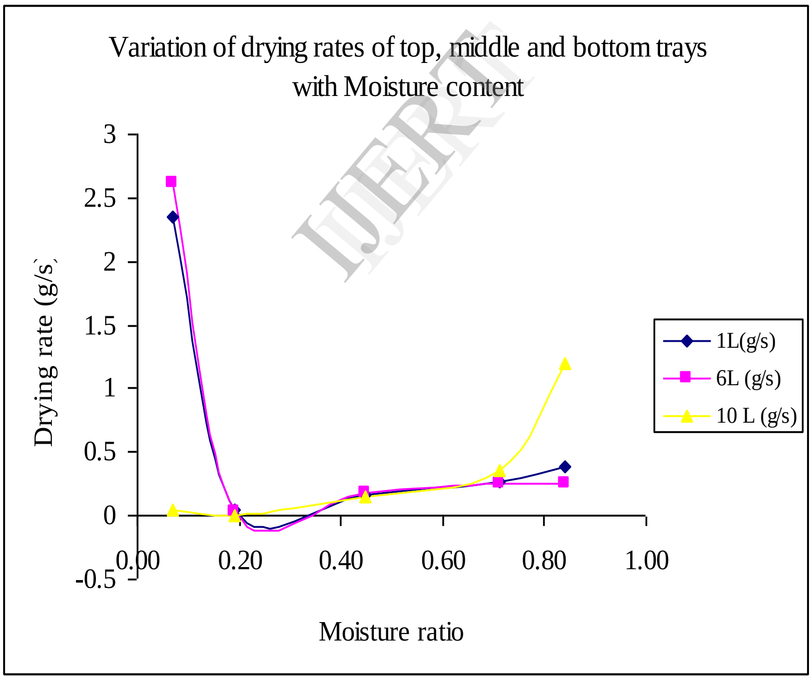


Figure 7: shows variation of drying rate with moisture content for top, middle and bottom trays

*Moisture Content of the kales*

The results (figure 6), indicate a reduction in moisture content of vegetable kales from an initial value of 84.14 % w. b. to 60 %, 54%, 48%, 28%, 24%, 22% and 14% for middle right, middle left, top left, bottom left, bottom right, top right trays and open sun respectively at the end of the first 6 hrs of drying. It is observed that the moisture ratio was further reduced on the second day from 46% to 10% in the middle right tray, from 38% to 20%, from 13% to 0% and from 13% to 2% in the middle right tray, bottom left, top right trays and the bottom right tray respectively, in the solar dryer and from 13% to 10% in open sun drying in a further 7 hours. It is observed that the final moisture content of kales attained is a function of the tray location; lower moisture contents were obtained in the top and bottom trays than in the middle during the first hours of drying. This can be explained by the fact that at the initial stage drying rate is controlled by the rate of evaporation of moisture from the surface of the kales, a process that wholly depends on external factors such as humidity, temperature and air flow rate. At the bottom of the chamber the humidity of air is minimum while temperature is maximum. The values of air flow rate and temperature at top trays near the chimney are also comparatively higher than those of the middle trays. It is observed that while a final moisture content of zero for kales was obtained in the solar dryer, the open sun dried samples attained a final moisture content of 10% in for a similar duration of drying. From figure 7 it is observed that at the initial stage of drying there is rapid decrease in the drying rate kales with moisture content followed by an increase and then a constant rate drying period.

*Drying rate constant (k)*

From the graphical plots of – In M. R. versus drying time (figure 12), the drying rate constants were computed for drying of kales in top, middle, bottom trays and for open sun drying and obtained as follows: 0.121 $hr^{-1}$(1R), 0.137$hr^{-1}$ (1L), 0.155 $hr^{-1}$ (6R) 0.144 $hr^{-1}$ (6L), 0.347 $hr^{-1}$(10R), 0.250 $hr^{-1}$(10L) and 0.0561 $hr^{-1}$(OS). Thus the mean drying constants for the top, middle and bottom trays were: 0.129 $hr^{-1}$, 0.150 $hr^{-1}$ and 0.299 $hr^{-1}$ respectively. It is deducible that drying rate constant varies with tray location in the dryer with bottom trays having the highest drying rate followed by the middle and top trays. It is also observed that open sun drying has the lower value of drying rate constant compared to solar dried kales.

*Effective moisture diffusivity ($D_{ef}$)*

The effective moisture diffusivity for Kales were computed according to equation 9, and found to be: $4.90\times10^{-8}$ $m^2/s$ (1R) and $5.55\times10^{-8}$ $m^2/s$ (1L) for top trays, $5.84\times10^{-8}$ $m^2/s$ (6R) and $6.28\times10^{-8}$ $m^2/s$ (6L) for the middle trays, $1.41\times10^{-7}$ $m^2/s$ (10R), $1.01\times10^{-7}$ $m^2/s$ (10R) for the bottom trays and $2.27\times10^{-8}$ $m^2/s$. The top trays had higher values compared to the middle and bottom trays. The mean effective moisture diffusivities of the kales are $5.23\times10^{-8}$ $m^2/s$, $6.06\times10^{-8}$ $m^2/s$ and $1.21\times10^{-7}$ $m^2/s$ for the top, middle and bottom trays respectively. It is observed that the effective moisture diffusivity of kales is highest for bottom trays and least in the top trays of the solar dryer. However the values of the effective moisture diffusivities of kales in the solar dryer were all greater than for open sun drying.

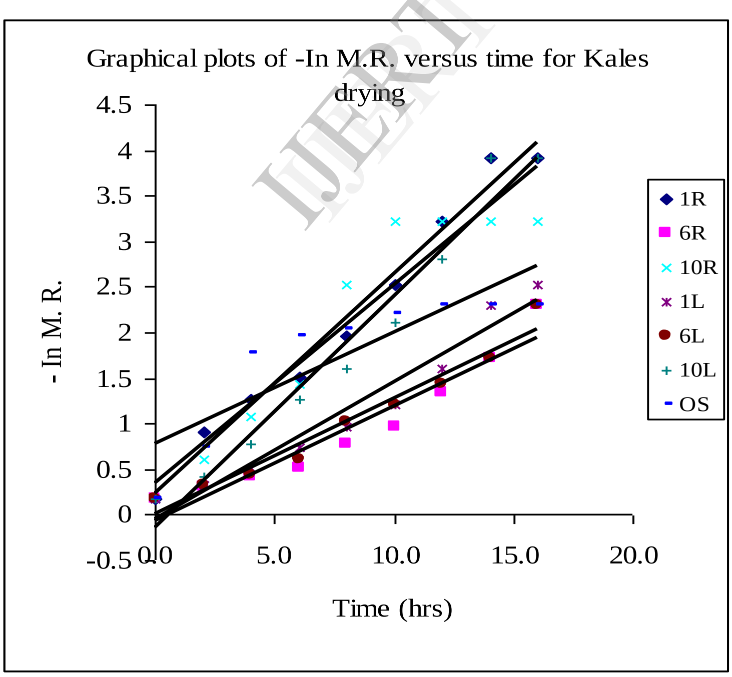


Figure 8: shows graphical plots of – In M. R. versus time for drying of Kales

*Quality tests*

The results of quality tests conducted on solar dried kales and control (wet) samples revealed that the content of Vitamin C in the solar dried kales was 90.9 mg per 100g as compared to 120mg per 100g in the wet samples, 76% being retained in the solar dried sample. The solar dried sample contained 4.275% tannius compared to 7.7 % in the wet sample, with 55% being retained in the dried sample.

The carbohydrate content was found to be 7.5 g per 100g as compared to 10 g per 100g in the wet samples, with 75 % being retained. The protein content was also tested in the solar dried sample and found to be 3.0 g per 100g as compared to 3.3 showing retention of 91 %. The mineral content in the solar dried sample were Ca: 130.0 mg/ 100g, Mg: 33.8 mg/ 100g, Fe: 1.7 mg/ 100g and Zn: 0.47 mg/ 100g, an almost 100% retention of these minerals.

Table 1: Results of quality test conducted on solar dried and wet vegetable kales

| Test | Wet sample | Solar dried sample | Comments |
|---|---|---|---|
| **Vitamin C** (Ascorbic acid ) for 11.87 m/s and 30 m/s sample Titers | 120mg per 100g | 90.9 mg per 100g | 76 % retained |
| **Tannius** | 7.8 % | 4.275 % | 55% retained |
| **Carbohydrates** | 10 g/ 100g | 7.5 g/100g | 75 % retained |
| **Protein** | 3.3 g/ 100g | 3.0 g/ 100g | 91 % retained |
| **Minerals** | Ca : 130.0 mg/ 100g<br>Mg: 33.8 mg/ 100g<br>Fe : 1.8 mg/ 100g<br>Zn : 0.48 mg/ 100g | 130.0 mg/ 100g<br>33.6 mg/ 100g<br>1.7 mg/ 100g<br>0.47 mg/ 100g | 100 % retained |

## CONCLUSIONS

The temperature of the drying chamber in the indirect natural solar dryer was increased by an average of 11.5 $^{o}$C above the ambient values while the relative humidity of air in the chamber was reduced by an average value of 31.4% at 0.39 m/s air flow rate for a mean incident solar radiation of 792 W/m$^2$ under no load conditions. The thermal efficiencies of the collectors were found to vary between 5 % and 25.5 %. Drying of Kales occurs in the falling and constant rate period with moisture content being reduced from 84.14% w. b. to less than 5.0 % w. b. and 10% in the solar dryer and open sun drying respectively in 13 hours. The overall quality and appearance of the solar dried kales was found to be good.



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