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Theme: Renewable Energy and Sustainability Experimental and Numerical Study of Drying of Moringa Oleifera Leaves

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Abstract: Drying is a preservation technique to reduce the water content of the food product to a safe level and to minimize biochemical reactions of the degradation and also to increase the shelf life of the product. Moringa being an agricultural product of high chemical, nutritional and medical use is susceptible to degradation due to relatively high moisture content. Moringa leaf is sensitive to sunlight, therefore, forced convection drying method with two types of air velocities (2.2 and 1.2 m/s) was employed in its drying. A batch of moringa leaves of 200g by mass having an initial moisture content of 83% wet basis was dried to desired 14% wet basis moisture content at average temperature of 40oC. Drying chamber and ambient temperatures, relative humidity, air flow velocity and rate of weight reduction were measured. The experimental and model results were statistically validated. Also numerical modeling of heat and mass transfer that occurred in the drying process was done using COMSOL Multiphysics 4.3b that uses finite element approach. It took between 10 and 12 hours to dry moringa leaves to the desired moisture content at drying air velocity 2.2 m/s and 1.2 m/s respectively. The results predicted from the modelling when compared with the experimental data have a considerably agreement.

Keywords: Drying, Solar dryer, Heat and mass transfer, Modeling, COMSOL Multiphysics

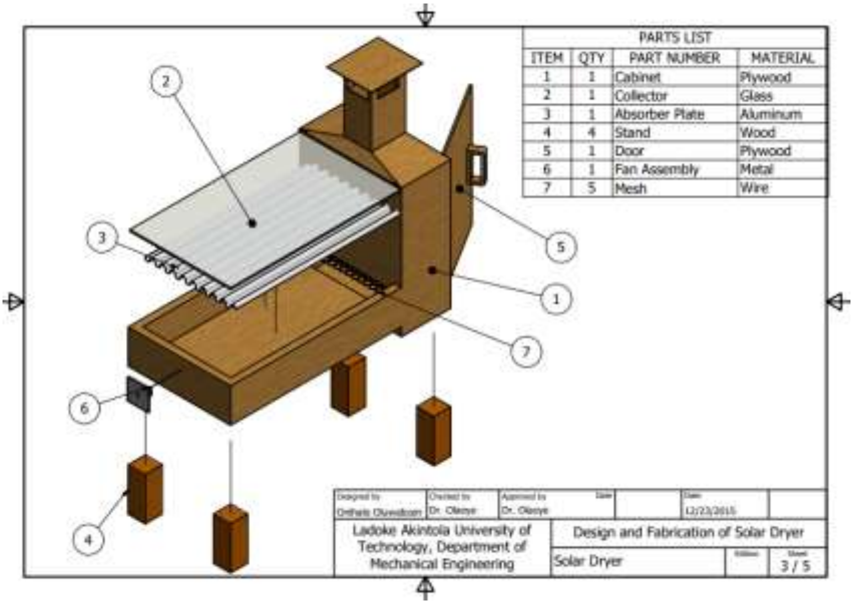
1. Introduction

Drying has been used from ancient times to preserve food products. Open-air drying is the most commonly used technique, especially in tropical and subtropical regions. The most common way to do this is to place the leaves on a mat, floors etc. and leave it in the open to dry. Drying of moringa leaves is a preservation activity done by farmers and herbal practitioners. It also affects the quality, nutritional values and the potency level of the leaves when exposed to the direct sunlight (Amedorme, et al., 2013 and Mujumdar, 2007). This process takes a long time and makes the leaves subjected to attack by the weather, animals and insects. However, because of the sensitivity of the leaves to direct sunlight, an indirect type of solar dryer was employed in this study. Thus, if the drying time can be reduced, the quality of dried product will be improved. Therefore, there is the need for an alternative drying methods such as those based on solar energy. The use of a solar dryer for drying can never be overestimated. In drying, many parameters influence the drying process and to be experimenting for optimizing of all these parameters may be costly (Curcio, 2006). Kumar et al (2012) considered variable properties of the material while simulation heat and mass transfer during drying using multiphysics. COMSOl was used to predict temperature and moisture distribution inside the food during drying. Hence a good drying model is essential for optimizing this process using computer simulation. Computer simulation is a powerful tool for achieving measurement of changes in temperature and moisture during dehydration process. Simulation results and information of drying kinetics of herbs material such as time, temperature, moisture content distributions, as well as theoretical approaches to moisture movement, is very essential for the prevention of quality degradation and for the achievement of fast and effective drying. Such information will be very useful to optimize production processes of herbs dried. The increasing development of computer program had a great impact on the quality evaluation of agricultural products (Rajibul and Norma, 2010).The objective of this study is to study the drying process of moringa using both experiment and numerical methods. The model consist of coupled heat conduction and mass diffusion equations which were solved using finite element method through the use of COMSOL Multiphysics 4.3

2. Method

2.1 Design considerations and features

The solar dryer was designed using locally sourced materials so as to reduce cost, increase ease of maintenance and operation. It consists of a heat collector which harnessed the radiation from the sun, an absorber which absorbed and saved the energy for use by the dryer, a drying chamber, three drying racks and a fan which transferred the heat to the drying chamber resulting in a forced convection. The dryer was an indirect solar dryer. The advantage of this is the protection of the leaves from loss of nutrients due to direct exposure to sunlight. The exploded view of the dryer showing its parts and materials used is shown in Figure 1.



PARTS LIST			
ITEM	QTY	PART NUMBER	MATERIAL
1	1	Cabinet	Plywood
2	1	Collector	Glass
3	1	Absorber Plate	Aluminum
4	4	Stand	Wood
5	1	Door	Plywood
6	1	Fan Assembly	Metal
7	5	Mesh	Wire

Fig 1: Schematic diagram of the dryer

2.2. Design equations

According to Amedorme, et al., (2013), the following equations were used in the design of the dryer.

The efficiency of the dryer was obtained using the following equations

$$\eta_d = \frac{ML}{I_c A_c} \tag{1}$$

Area of the drying rack obtained by the following equations

$$A_{rac} = \frac{M_p}{P_{gr} h_L \varepsilon (1 - \varepsilon_v)} \tag{2}$$

Applying Bernouli's equation between the relevant sections of the dryer and sampling the results leads to height of the drying chamber

$$H = \frac{\Delta P_T}{g\left(\frac{1}{T_a} - \frac{1}{T_o}\right)\frac{P_a}{R}} \tag{3}$$

According to Bolaji (2005), the height difference between the inlet air and exhaust of a forced convention should not exceed 1200 mm with collector area less than 10

Chimney height, $hc = 1.2 - (0.75 + 0.1) = 0.35m$ (4)

2.3. Solar Dryer Dimensions

The heat absorber (inner box) of the solar air heater was constructed using 2mm thick aluminum plate, painted black, and was mounted in an outer box built from well-seasoned odum and plywood. The space between the inner box and outer box was filled with foam material of about 40mm thickness and thermal conductivity of 0.043Wm-1K-1.

The solar collector assembly consisted of air flow channel enclosed by transparent cover (glazing). The glazing was a single layer of 4mm thick transparent glass sheet; it had a surface area of 1000mm by 600mm and of transmittance above 0.7 for wave lengths in the rage 0.2–2.0µm. One end of the solar collector had an air inlet vent of area 0.0457m2, it was fitted with fan to provide the forced convection, and the other end is opened to the drying chamber.

An outlet channel was fitted with chimney. Access door to the drying chamber was provided at the side of the cabinet. Drying trays was contained inside the drying chamber and constructed from a double layer of fine wire mesh with a fairly open structure to allow drying air to pass through the moringa leaves. The flat-plate solar collector was tilted and oriented in such a way that it will receive maximum solar radiation during the desired season of use. It was inclined at 18.13o according to Ogbomoso Latitude (8.13o) the angle of inclination must be 10o more than the local geographical latitude for best all year performance (Bolaji, 2005). The capacity of the dryer is 200g of moringa leaves.

2.4. Experimental procedure

Fresh moringaoleifera leaves were obtained from farms in Ogbomoso, South Western Nigeria. They were sorted, washed and dried using the dryer. During the drying process, the temperature of the absorber, collector, drying chamber and air leaving the chimney were measured and recorded at a time interval of 20 minutes. Also, the mass of the product was measured and recorded every hour so as to track the rate at which moisture was reduced and obtain a moisture profile for the drying process. The thermal properties of moringa were obtained at different room temperature (27.43 , 27.15 and 26.85) using KD-2 pro thermal analyzer. The experiment was done three times and the average results were recorded. The solar radiation at the time of the experiment was measured using solar power meter (LT Spm – 1116SD). The experiment was carried out for an average of 2 days before obtaining a dried product.

2.5. Mathematical Model:

In developing the model, the following assumptions were made:

(1) Thermophysical properties of the moist material and drying air are constant.

(2) There is negligible shrinkage or deformation of material during drying.

(3) Drying air is distributed uniformly through the dryer

(4) Heat and moisture transfer are one dimensional

(5) No chemical reaction takes place during drying

2.5.1. Governing equations:

Drying kinetics can be modeled mathematically based on Fick's law of diffusion. The simulation of various product drying systems involves solving a set of heat and mass transfer equations.

The first drying process is heat transfer to the product from the heating source and the second is mass transfer from the interior of the material to its surface and from the surface to the surrounding air.

Heat transfer equation

$\rho_s Cp_s \frac{\partial T}{\partial t} + \nabla\left(-k_s \nabla T\right) = Q_s$ Faghri, *et al.*, 2010) (5)

$$\hat{r}^2 \rho_s Cp_s \frac{\partial T}{\partial t} + \frac{\partial}{\partial r}\left(-\frac{1}{{R_m}^2} k_s \hat{r}^2 \frac{\partial T}{\partial r}\right) = \hat{r}^2 Q_s \qquad (6)$$

In a similar manner it is possible to derive equation similar to equation 3.21 for porous media flow, diffusion-reaction problems and so on.

Mass transfer equation

$$\frac{\partial M}{\partial t} + \nabla(-D\nabla m) = \dot{m}_s{}^{II}$$

(Faghri, *et al.*, 2010) (7)

$$\hat{r}^2\frac{\partial M}{\partial t} + \frac{\partial}{\partial \hat{r}}\left(-\frac{1}{R_m{}^2}\nabla\hat{r}^2\frac{\partial M}{\partial r}\right) = \hat{r}^2\dot{m}_s{}^{II} \quad (8)$$

Due to symmetry about r = 0, there is zero flux through this point meaning $\frac{\partial}{\partial \hat{r}} = 0$

At the surface, $\hat{r} = 1$, a convective heating expression was used with heat transfer coefficient h_s(W/m^2K) for the influx of heat (W/m^2): $q_{in} = h_s(T_{air} - T)$

(9)

Initial moisture content, M_0= 80%, initial temperature T_0= 27°C

Heat transfer boundary conditions:

At open boundary: (k∇T) = h_s ($T_{air} - T$)

At symmetry and other boundary: (k∇T) = 0

Mass transfer boundary conditions:

At open boundary: (D∇M) = h_m ($M_m - M$)

At symmetry and other boundary: (D∇M) = 0

2.5.2 COMSOL Implementation

The 1D time dependent version of the General form PDE equation system was used to implement the heat and mass transfer equation

$$e_a\frac{\partial^2 u}{\partial t^2} + d_a\frac{\partial u}{\partial t} + \nabla.\Gamma = \text{F in } \Omega, \quad (10)$$

$$\text{n}.\Gamma = \text{G} - \text{hT}\mu \text{ on } \partial\Omega, \quad (11)$$

$$0 = \text{R} \text{ on } \partial\Omega. \quad (12)$$

The space coordinate in the model is $\hat{r}$. For typographical reasons r_h was used for "r-hat". Using radial coordinate to rewrite the heat and mass transfer equation and identifying the general form, the following setting shown in Table 1 generates the correct equation;

Table 1: Equations Generated for Comsol Implementation.

Coefficient	Expression (Temperature)	Expression (Moisture)
e_a	0	0
d_a	$\hat{r}^2\rho_s Cp_s$	$\hat{r}^2$
Γ (flux vector)	$-\frac{1}{R_m{}^2}k_s\hat{r}^2\frac{\partial T}{\partial r}$	$-\frac{1}{R_m{}^2}\nabla\hat{r}^2\frac{\partial M}{\partial r}$
F (source term)	0	0

Special care was taken when setting the heat flux boundary condition on the moringa leaf surface h_s ($T_{air} - T$) = $k_s\frac{\partial T}{\partial r}$, so G needs to be accordingly compensated.

$$\text{G} = \frac{\hat{r}^2}{R_m{}^2}h_s(T_{air} - T) \quad (13)$$

$$\text{G} = \frac{\hat{r}^2}{R_m{}^2}h_m(M_m - M) \quad (14)$$

3. Results and Discussion:

3.1. Thermal Properties Results

The results of thermal properties are presented in Table 2. From the results presented in the table the highest properties were obtained at 27.15°C and can also be seen that temperature affects thermal properties of the moringa.

Table 2: Properties of moringa of obtained experimentally.

Temperature (°C)	Thermal Conductivity [W/m.K]	Diffusivity [m^2/s]	Specific Heat [J/kg.K]	Moisture content [%]
27.43	0.506	0.162	3.130	82.876
27.15	0.517	0.194	2.668	82.488
26.85	0.482	0.156	3.098	82.727

The moisture profile of the product with time is shown in Fig. 3 for drying at a velocity of 2.2m/s and 1.2m/s. It is evident that moisture content is reduced faster at a higher velocity.

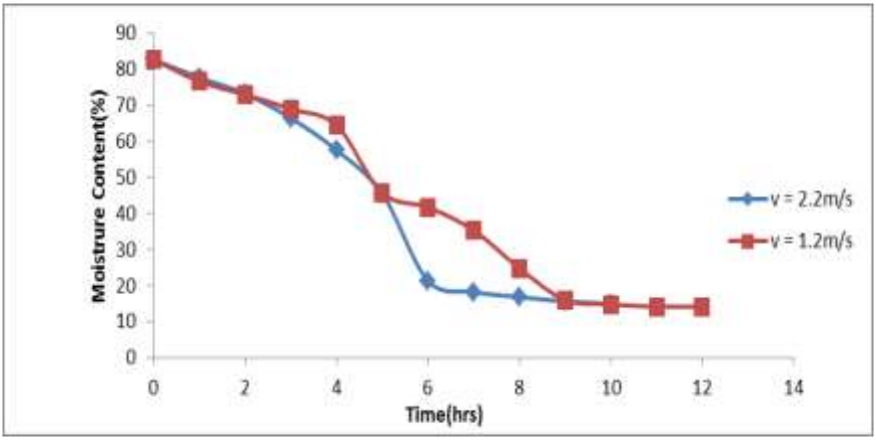


Fig 3: Moisture profile at different velocities (v=2.2m/s and v=1.2m/s).

Figure 4 represents the moisture content with drying time for the three trays in the drying chamber at a velocity of 2.2m/s. It shows that products in tray 3 give off moisture faster than any of the other two trays (moisture reduced up to 65% in about 4 hours). This is because it is the closest to the absorber. The air flowing to it has very low humidity and has the highest temperature, making it possible for moisture to leave at the highest rate. Tray 1 dries moisture faster than tray 2 but not as fast as tray 3. This is because it is the farthest from the absorber but the closest to the chimney opening. Being close to the chimney opening makes it possible for air to leave the tray faster than the rate at which it leaves tray 2.

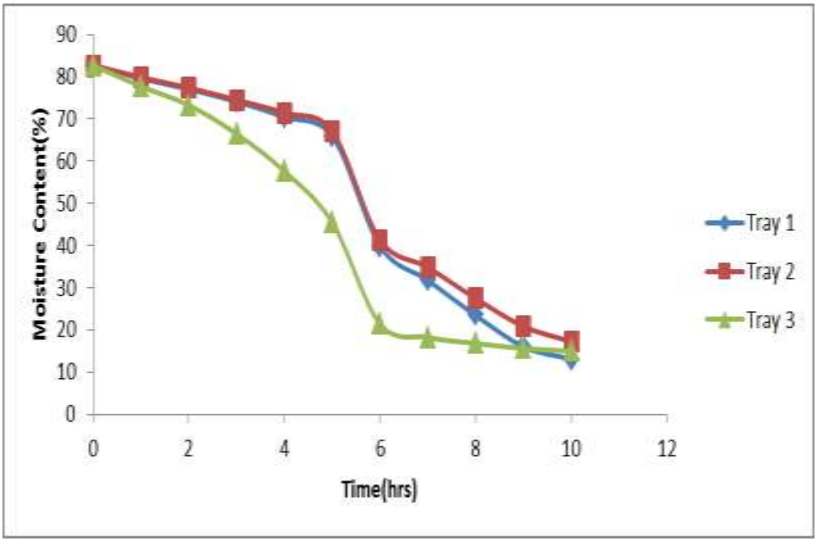


Fig 4: Moisture profile for tray 1, 2 and 3 (for v=2.2m/s)

It is evident from Fig. 5 that a higher velocity leads to a higher temperature of the product. It also results in high rate of increase in temperature. This is due to the fact that heat is diffused faster when the speed at which air is moving is higher. The moisture leaving the product are also transported faster at higher speed, leading to high reduction rate in moisture content and consequent increase in temperature of the product.

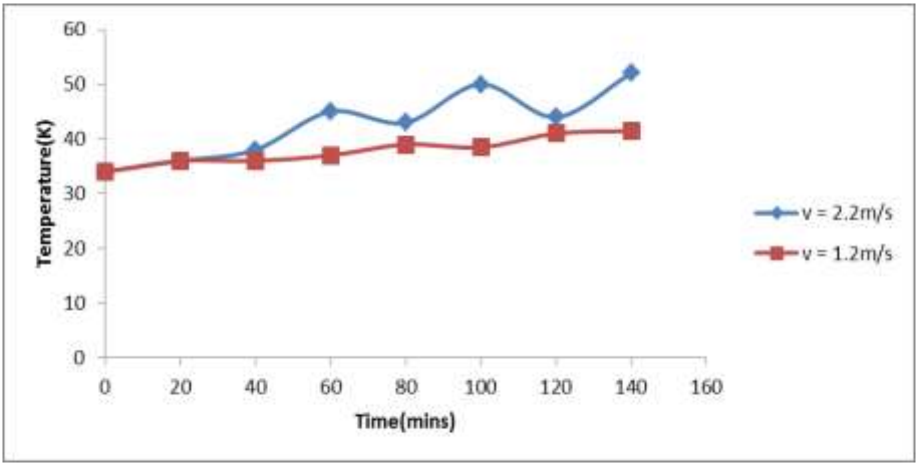


Fig 5: Temperature profile obtained at different velocity (v=2.2m/s and v=1.2m/s).

3.2. Comparing Simulated Results with Experimental Results

The temperature evolution of the product is shown in Figs. 6 and 7 for velocity of 2.2m/s and 1.2m/s respectively with a mean drying air temperature of 45°C. It can be seen that the predicted temperatures agreed with those obtained experimentally at some points and deviated a little at some other points. This may be as a result of certain human factors and challenges incurred during the experimental procedure.

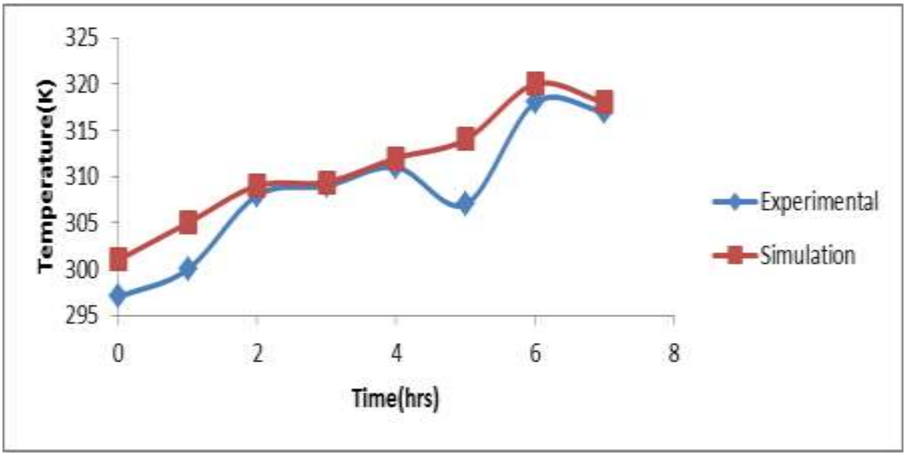


Fig 6: Temperature profile obtained for experimental and simulation procedures (for v=2.2m/s).

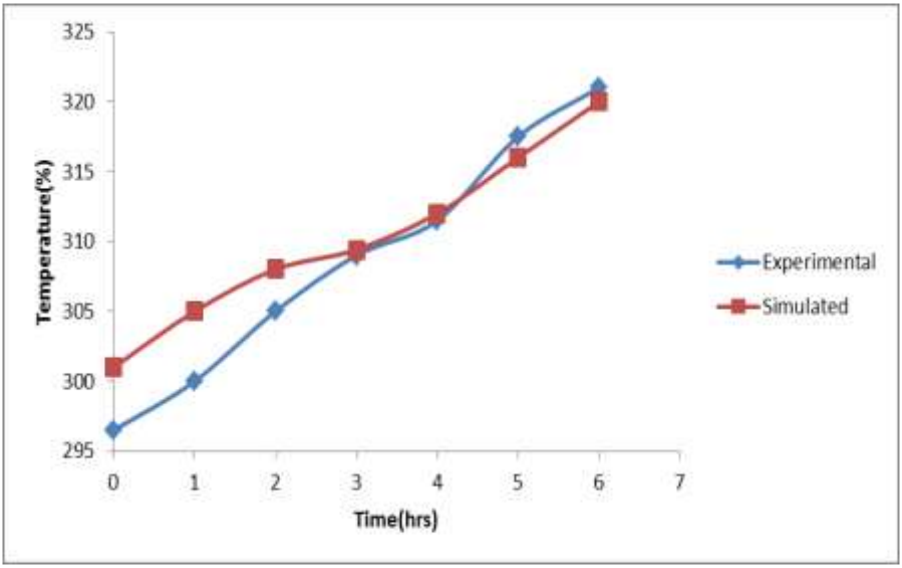


Fig 7: Temperature profile obtained for experimental and simulation procedures (for v=1.2m/s).

The moisture content with drying time is represented in Figs. 8 and 9 for velocity of 2.2m/s and 1.2m/s respectively. It shows that the simulated results and predictions are in accordance with experimental results at a velocity of 2.2m/s.

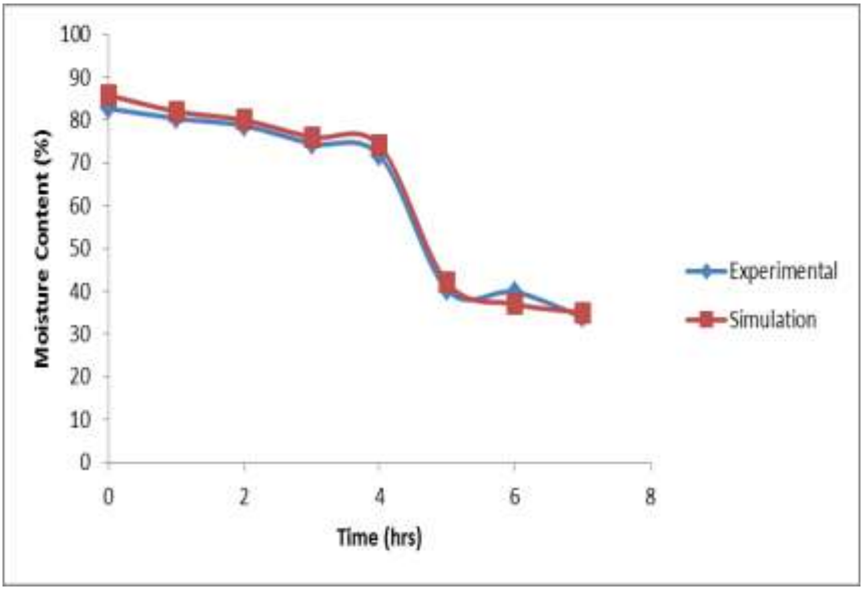


Fig 8: Moisture profile obtained for experimental and simulation procedures (for v=2.2m/s)

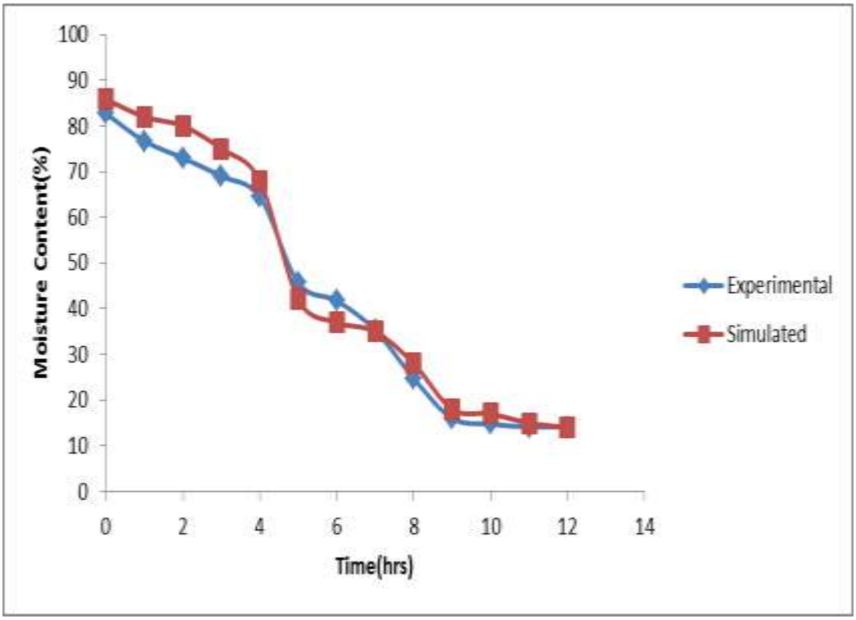


Fig. 9: Moisture profile obtained for experimental and simulation procedures (for v=1.2m/s)

4. Conclusion

Moringa leaves were successfully dried using the designed and fabricated dryer. The dried product obtained supports the fact that the solar dryer performs better than open air drying for drying moringa. This is seen in the physical appearance of the product and the increased rate of drying the leaves. The best product was obtained when performing the drying process at a velocity of 2.2m/s due to the fact that products dried faster and looks better than when performing it at a velocity of 1.2m/s.The simulated and experimental results revealed that the rate of drying is increased at a higher velocity. These results are also similar, which indicates that simulating the drying process can be as effective as performing the experiment with a dryer. Solar dryer was perceived to be an effective equipment for drying leaves.

5. Nomenclature

η_d	Efficiency of the dryer
M	Mass of moisture evaporated per second (kg/s)
L	Latent heat of evaporation of water (kJ/kg)
I_t	Insolation on tilted collector surface (W/m^2)
A_c	Collector area (m^2)
$Arac$	Effective drying rack area
M_p	Mass of moringa,
P_{gr}	Bulk density of moringa on wet basis,
h_L	Depth of drying rack,
ϵ	Crop porosity,
ε_v	Loading bed void fraction,
T_a	Temperature of drying air leaving the collector,
ρ_s	Density of solid (kg/m^3)
Cp_s	Heat capacity of solid (J/kgK)
k_s	Thermal conductivity of solid (W/mK)
Q_s	Internal heat source (W/m^3)
R	Specific gas constant,
T_0	Temperature at collector outlet
T_a	Temperature of drying air leaving the collector,
g	Acceleration due to gravity
H	Height of the drying chamber
P_a	Atmospheric pressure

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