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Design, Construction And Testing Of A Moringa Oliefera Mixed-Mode Cabinet Solar Dryer

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ABSTRACT: *Different drying techniques for drying agricultural products were reviewed in this study with an objective of developing a suitable solar dryer for drying Moringa Oliefera leaves. An experimental Moringa Oliefera Mixed-mode cabinet solar dryer was designed, constructed and tested. The dryer which has a drying cabinet area of 1.46m*^{2} *and a collector area of 1.10m*^{2} *was used to dry* $5.0\pm0.01kg$ *of moringa leaves. Maximum temperature of* 40.0 ± 1.0°C *was recorded inside the drying cabinet throughout the test period to comply with medicinal considerations. The time taken by the solar dryer to reduce the moisture content of Moringa from 73.2% to 9.0% is 20 hours as compared to 96 hours (4 days) in open-air or natural sun drying. In addition, the effectiveness of the dryer was further confirmed by other tests which indicated that more moisture was removed by this design than the other method of drying as much liquid was removed from the Moringa leaves leaving the final mass of initial 5kg to be* $0.8\pm0.01kg$ *– compare with that of the conventional method where the final mass was 1.2kg. These values predicate that products dried by this design will have a longer storage life over others dried with other methods. Obviously, this mixed-mode cabinet solar Moringa dryer has also overcome such other disadvantages of exposing the Moringa to weather elements like dust, rain, wind and overly hot ambient temperatures. The designed dryer also shielded the products from disease carrying vectors like insects, rodents and domestic animals in contrast to the traditional open sun drying methods. This technology has contributed a fast and hygienic method that reduces wastage during solar drying of products to the economy.*

SIGNIFICANCE: *This Design presents a better option of preservation of Moringa Oliefera leaves to farmers all over the world. It furthers help to reduce the traditional drying time and overcome disadvantages such as exposure to dust, rain and wind, insects, birds, rodents and domestic animals while drying, Soiling, contamination with micro-organisms, formation of mycotoxins, and infection with disease-causing germs which results from the traditional open-air method of drying.*

KEYWORDS: *Moringa Oliefera, Energy, moisture content, Drying cabinet.*

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NOMENCLATURE

M_w = Amount of moisture to be removed from the Moringa (%)
W_m = weight of moist product to be dried (kg)
W_d = weight of the dried product (kg)
W = percentage moisture content, dry basis of the sample of the product (%)
m = total mass of the sample (kg)
M = moisture content in dry sample (kg)
$\mathbf{a}_w$ = water activity (Relative humidity), (decimal)
m = moisture content, dry basis, (kg water/ kg dry solid)
$ø_{eq}$= Equilibrium relative humidity (%)
E = Quantity of heat (kJ)
Ma= mass of the air (kg)
T_1 = Ambient temperature (^{O}C)

T_2 = collector's temperature (^{O}C)
Q_L= heat loss (kJ)
∂_{ES}= Dirac function
G = Total global radiation on the horizontal surface during drying period (W/m^2)
Ac = Area of Solar collector (m^2)
t_d= drying time (s)
R = Resistance of the filament (Ω)
I = current (A)
η_c = collector's efficiency (%)
Tpr= product temperature (^{O}C)
$\dot{m}_a = massflowrate$of air (kg/s
$hi = initialenthalpy\ (kJ/kg)$
$h_f = finalenthalpy$ (kJ/kg)
$\eta = relativehumidity$ (%)
$P = Atmosphericpressure\ (\ bar)$
$P_{sat} = Saturatedpartialpressureofmoisture\ (bar)$
$\eta_d = Dryerefficiency$ (%)
$\dot{m}_{dr} = Rateofevaporation\ (kg/s)$
$w_i, w_f = initialfinalabsolutehumidityrespectively, (kgH_2O\ /kgdryair)$
$\dot{V}_a$ = Volumetric air flow rate (m^3/s)
$\rho_a = airdensity$ (kg/m^3)
$A_v = Areaofairvent$ (m^2)
$U_w = windvelocity$ (m/s)
$V_f = fanvelocity$ (m/s)
$L_v = Lengthofairvent$ (m)
$\dot{Q}_L = rateofheatlossfromthedryer$ (kJ/s)
$h = Averageconvectiveheattransfercoefficient$ (W/m^2)
$A = areaofthedryingcabinet$ (m)
$T_e = Exittemperaureofair$ (^{O}C)
$T_a = Ambienttemperature$ (^{O}C)
$k = thermalconductivity$ (W/m ^{O}C)
$Nu_L = Nusseltnumber$
$Re_L = Reynoldsnumber$
$C_p = specificheatcapacityofair$ (kJ/kg ^{O}C)
$\mu = Dynamicviscosity$ (Ns/m^2)
$v = vinematicviscosity$ (m^2/s
$L = lengthofdryer\ (m)$
$sh = sherwoodnumber$
$D_c = DiffusionCoefficient$ (m^2/s)
h_{cc} = mass transfer coefficient (m/s)
T = temperature of the drying cabinet, assuming the water and cabinet to be in equilibrium, K.
Sc = Schmidt number
C_w = Concentration of the water from the Moringa (kg/m^3)
C_o = Concentration of water vapour in air (kg/m^3)
$P_{sat}\,(T) = Saturatedpressureformoistureatdryertemperature$ (N/m^2)
$P_v = Vapourpressureofwaterintheairtemperature$ (N/m^2)
$r_w = Gasconstantformoisture$ (J/kgK)
$r_a = Gasconstantforair$ (J/kgK)
$T_w, T_a = moistureandairtemperaturerespectively\ (K).$

I. INTRODUCTION

Traditional drying methods for fruits and vegetables in rural areas in Nigeria is to spread the product on the ground with exposure to the sun in the open air. This has advantages of being the simplest and cheapest method of conserving agriculture produce. However, the disadvantages of open air drying are: exposure to direct sunlight, which is undesirable for some food products, uncontrolled drying, exposure of the food product to rain and dust, infestation by insects and bacteria, effect by rodents and other animals, e.t.c., (Madhlopa et al., 2002).

Sun drying remains the most common method used to preserve agricultural products in most Tropical Sub-tropical countries thereby accelerating the time for drying and controlling the final moisture content of the products. The agricultural product exposed to the open air may be seriously degraded to the extent that sometimes it becomes inedible and the resultant loss of food quality in the dried products may have adverse economic effects on domestic and international markets. Some of the problems associated with open- air sun drying can be solved through the use of a solar dryer, which comprises of a collector, a drying chamber and sometimes a chimney. (Madhlopa et al., 2002). Also, the improvement of product quality, reduction of losses through wastage and bacterial action can only be achieved by the introduction of suitable drying technologies.

II. LITERATURE REVIEW

2.1 SOLAR DRYING:

Drying is an excellent way to preserve food and solar food dryers are an appropriate food preservation technology for a sustainable world. Actually, solar food drying is one of the oldest agricultural techniques related to food preservation, but every year, millions of dollars' worth of gross national product are lost through spoilage. Reasons include, ignorance about preservation of produce, inadequate transportation systems during the harvest season (mostly climate related), and the low price the rural farmer receives for products during the harvest season.

Drying of crops can change this trend and is useful in most areas of the world, especially those without a high humidity during the harvesting season. If drying of produce were widely implemented, significant savings to farmers would be achieved. These savings could help strengthen the economic situation ofnumerous developing countries as well as change the nutritional condition in these same countries. Unfortunately many of the areas that could benefit from solar drying technology lack adequate information related to how to employ this technology and which technology to use under specific conditions (David, 2000).

Solar Drying preserves products by removing enough moisture from it in order to prevent decay and spoilage. Water content of properly dried food and vegetable varies from 5 to 25 percent depending on the food. Successful drying depends on:enough heat to draw out moisture, without cooking the food;dry air to absorb the released moisture; andAdequate air circulation to carry off the moisture.

When drying foods, the purpose is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavor, texture and color of the food. If the temperature is too low in the beginning, microorganisms may grow before the food is adequately dried. If the temperature is too high and the humidity too low, the food may harden on the surface. This makes it more difficult for moisture to escape and the food does not dry properly. Although drying is a relatively simple method of food preservation, the procedure is not exact (David, 2000).

Renowned solar cooker designer and Sustainable Living expert Kerr, (1999) tells us that, "food drying is a very simple, ancient skill. It requires a safe place to spread the food where dry air in large quantities can pass over and beside thin pieces. Sun is often used to provide the hot dry air.

2.2 **IMPORTANCE OF SOLAR DRIED PRODUCTS**

Dried foods are tasty, nutritious, lightweight, easy-to-prepare, and easy-to-store and use. The energy input is less than what is needed to freeze or can, and the storage space is minimal compared with that needed for canning jars and freezer containers (David, 2000);

The nutritional value of food is only minimally affected by drying. Vitamin A is retained during drying; however, because vitamin A is light sensitive, food containing it should be stored in dark places. Yellow and dark green vegetables, such as peppers, carrots, winter squash, and sweet potatoes, have high vitamin A content. Vitamin C is destroyed by exposure to heat, although pretreating foods with lemon, orange, or pineapple juice increases vitamin C content (David, 2000);

Dried foods are high in fiber and carbohydrates and low in fat, making them healthy food choices. Dried foods that are not completely dried are susceptible to mold;

Microorganisms are effectively killed when the internal temperature of food reaches 145 degrees Fahrenheit (62.1^{o}C)

Food scientists have found that by reducing the moisture content of food to between 10 and 20%, bacteria, yeast, mold and enzymes are all prevented from spoiling it. The flavor and most of the nutritional value is preserved and concentrated. Vegetables, fruits, meat, fish and herbs can all be dried and can be preserved for several years in many cases. They only have 1/3 to 1/6 the bulk of raw, canned or frozen foods and only weigh about 1/6 that of the fresh food product. They do not require any special storage equipment and are easy to transport (Scanlin, 1997).

2.3 SOLAR DRYERS

A Solar dryer is an enclosed unit that is used to keep food safe from damages, from birds, insects, and unexpected rainfall. The food is dried using solar thermal energy.

Types of Solar Dryer

According to Baker and Christopher (1997) there are three types of solar dryers and they are classified according to the type of energy used.

- Solar natural dryers;
- Semi-artificial dryers;
- Solar-assisted dryers

Solar Natural Dryers: These devices use only ambient energy and have no active elements. The air flow, if there is any, is maintained by natural convection or, in some cases, by thermo-syphon effects induced by a chimney. Solar natural dryers are mainly used as substitutes for traditional open-air drying methods in areas where no other source of energy is available. (Vaipulu, 2009).

Types of Solar Natural Dryers

(a) Cabinet dryers.

These are the simplest and cheapest types of solar dryer. They are generally used for drying agricultural products, such as fruits, herbs, vegetables, and spices, in small quantities (Wibulswas and Niyomkarn, 1980), (Reuss, 1993) cited in
(Baker and Christopher, 1997).

Figure 1 below, shows a schematic diagram of a Cabinet dryer.

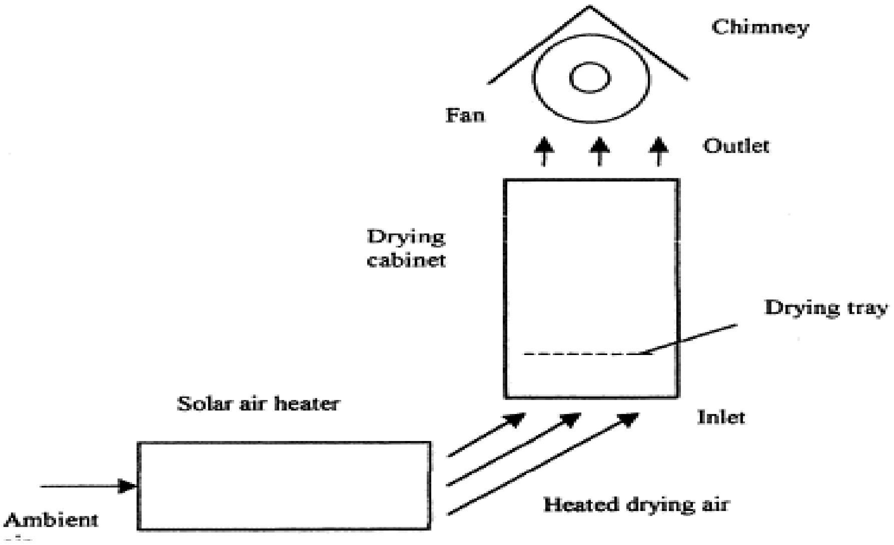

Fig. 1. Schematic diagram of a solar cabinet dryer.

From the diagram in figure1, the ambient air were drawn into the dryer by the flow produced by the fan, and warmed in the heater before entering the cabinet to dry the produce. After drying, the moist air from the drying cabinet is sucked out by the fan through the chimney.

(b) Tent type dryers.

The drying capacity of cabinet type dryers can be increased by enlarging the basic surface area of the dryer. Tent type dryers represent the simplest and cheapest way to achieve this goal. The drying space is located within a tent, which may have a triangular or semi-circular cross-section. The material to be dried is spread on a perforated tray or directly on a concrete floor (Sunworld, 1980).

Semi-artificial solar dryer: These usually feature a solar collector and a fan for maintaining a special air flow through the drying space. In the case of directly irradiated solar tunnel dryers, a section of the tunnel may be employed as a transparent plastic covered solar collector (Imre, 1989, 1995); (Lutz and Muhlbauer, 1986) cited in (Baker and Christopher, 1997). The use of semi-artificial solar dryers is justified by their unsophisticated and fairly cheap construction.

2.4 MORINGA OLIEFERA

Moringa oleifera is called “Miracle Vegetable” because it is both a medicinal and a functional food (Verma *et al.*, 1976). The leaves are the most nutritious part of the plant, being a significant source of vitamin B_6, vitamin C, provitamin A as beta-carotene, magnesium and protein, among other nutrients (Peter, 2008). When compared with common foods particularly high in certain nutrients, fresh moringa leaves are considerable sources of these same nutrients (Fuglie et al., 1999). Almost all the parts of this plant root, bark, gum, leaf, fruit (pods), flowers, seed and seed oil have been used for various ailments in the indigenous medicine of South Asia, including the treatment of inflammation and infectious diseases along with cardiovascular, gastrointestinal, hematological and hepatorenal disorders (Morimitsu *et al.*, 2000). The flowers and roots are used in folk remedies, for tumors, the seeds for abdominal tumors, leaves applied as poultice to sores, rubbed on temples for headaches and are said to have purgative properties (Anwar *et al*., 2007). The leaves are cooked and used like spinach. In addition to being used fresh as a substitute for spinach, its leaves are commonly dried and crushed into a powder used in soups and sauces. It is important to remember that like most plants, heating moringa above 140 degrees Fahrenheit (60°C) will destroy some of the nutritional value (Wikipedia).

Because of these numerous functions and benefits of Moringa Oliefera leaves, it requires hygienic preservative methods at a regulated temperature and relative humidity, hence, the design, Construction and testing of a Moringa Oliefera mixed-mode cabinet solar dryer.

III. MATERIALS AND METHODS

3.1 Description of the Solar Dryer

The basic mechanism of material drying is one of heat and moisture transfer between the material and the air. The heat is transferred to the surface of material by conduction and convection from adjacent air at temperature above that of the material being dried. If the air is passed through the material at a relative humidity of less than moisture content in material, the air will absorb moisture from the material while increasing its absolute and relative humidity.

A unit Moringa Oliefera Mixed mode cabinet solar dryer has been designed, constructed and evaluated and is shown in Figure 6. The unit is made up of Collector, Drying chamber and a Chimney.

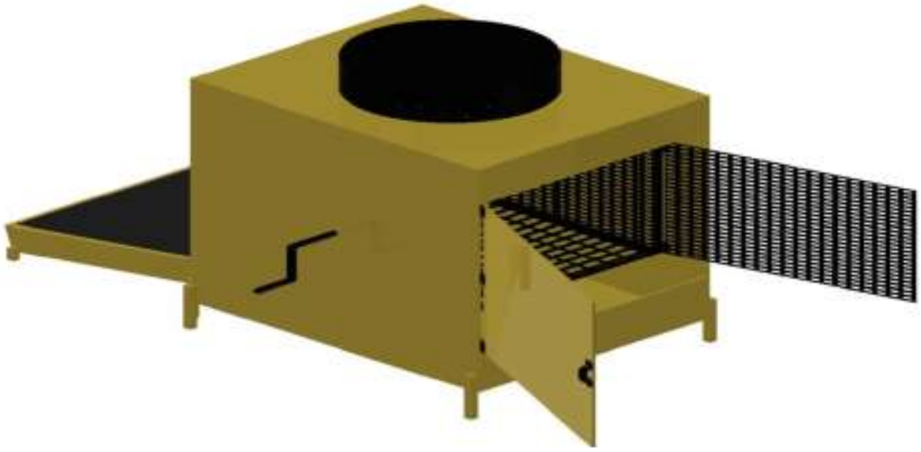

Figure 6: Moringa Mixed mode cabinet solar dryer

The Solar Collector with dimension 1.1m length, 1.1m width and 0.2m height was made from a mild steel of 1.5mm thickness and painted black to increase the absorbency. The system is framed with 20mm wooden logs. A single layer of typical glass cover of 4mm thickness is applied on the top surface of the collector with the help of iron clips and screws. The collector is insulated with saw-dust material to minimize the heat loss from the collector. An air vent of 0.03m is created in the front and backside of the collector so that heated air can pass through into the dryer. The Solar collector system was positioned to face southwest and tilted 12^o from the horizontal level. The direction was chosen to ensure wind flow is perpendicular to vent entry.

The drying chamber with dimension 1.2m x1m x1.2m was constructed with mild steel wire mesh of 145mm which served as a frame. The inside and outside of the wire mesh frame were covered all through with Teflon net in order to prevent the Moringa leaves from having direct contact with mild steel since the leaves are edible. The drying cabinet was mounted on a dryer housing with two bearings that enable the dryer to rotate and 4 bolts and nuts which serve as a fastener. The dryer housing is also made with a mild steel of 0.5mm and its dimension is given as 1.33m x2m x1.35m. The front of the dryer housing is covered with a glass of thickness 4mm to enable a viewer to view the product directly.

Directly above the drying chamber inside the dryer housing is a fan with speed 1020 r.p.m mounted to suck away the moist air out through the Chimney placed above the dryer housing. The presence of the fan also helps to eliminate moisture thereby reducing the relative humidity from the dryer and suck in warm air from the collector.

Mode of Operation

The warm air outlet of the collector is connected to the front side of the dryer housing. The Moringa leaves to be dried are spread on the Teflon net inside the dryer and solar heated air from the collector passes through the drying housing to the dryer to dry the Moringa. To increase the air circulation rates, wind-operated ventilator (fan) placed in the Chimney is switched on.

As the drying process continues, the Moringa leaves inside the dryer are turned over and over using the handle attached to the dryer for even circulation of air in the dryer from time to time until the produce is completely dried.

3.2 MATERIALS

The materials used for the construction of the Moringa Oliefera Mixed-mode cabinet solar dryer system are cheap and easily obtainable in the local market. Figure 6 shows the essential features of the Moringa Mixed –mode cabinet solar dryer, consisting of the solar collector (air heater), the drying cabinet and a chimney containing a fan.

The materials used for the collector system are 1.5mm thickness mild steel sheets, 4mm thickness glass, welding electrode, 20mm wooden logs, saw-dust(insulator), iron clips, screws and nails.

The drying cabinet is made from mild steel wire-mesh of 145mm which was used for the frame, Teflon net, 0.5mm thickness mild steel sheet used in making the dryer housing, bearings, 4mm glass thickness, bolts and nuts.

The chimney is made from 0.5mm mild steel sheet, while the fan is made up of Electric motor and brass rotor, plastic blade and nut.

3.2.1 DESIGN ANALYSIS

Design Data / Specification:

The design data/specification for the Moringa dryer are:

To dry 5 kg of Moringa Oliefera from initial water content of 73.2% to a recommended moisture level of 9%

To provide a drying method that will help preserve the products from Contamination such as dirt, insects, bacteria, Fungi etc.

To accelerate the traditional drying time of Moringa Oliefera leaves from 144 hours to about 48 hours or less.

Fan Specification, d = 385mm, V_r = 1020 r.p.m, 240V, f = 50Hz,(from market).

Maximum fan velocity, V_f = 20.6m/s; and minimum fan velocity when used with regulator, V_{mf} = 5.0m/s

3.2.2 Design Considerations

The following feature were considered in the design of the system:

The amount of moisture to be removed from a given quantity of wet Moringa Oliefera.

The daily sunshine hours for the determination of the total drying time;

The quantity of air needed for the drying;

Daily solar radiation to determine energy received by the dryer per day;

Heat losses from the dryer.

Moisture Content: The moisture content of a product may be expressed on either the wet-weight basis or dry basis. For this research work, moisture content on dry basis is being used since it has the advantage that the moisture loss is obtained by subtracting the moisture contents before and after drying. Moisture content on wet-weight basis expresses the moisture in the material as percentage of the weight of the material (kg/kg wet material) and is mathematically given by (Rauf, 2000)

$$Moisture content (\%) = \frac{Weight of the water in the moist product}{Weight of the moist product} X\ 100$$

This can also be expressed as:

$$m_w = \frac{(W_m - W_d)}{W_m} X\ 100 \quad \ldots\ldots\ldots\ldots\ldots (1a)$$

The percentage moisture content, W (%), (dry basis) of the sample product is defined by:
$W = \frac{m-m_d}{m_d} X\ 100$ …………………. (1b)
The moisture content in 1kg of Moringa leaves is calculated using equation (1a);
$m_w = \frac{w_m - w_d}{w_m} x100,$

$$w_m = 1kg$$

$w_d = 0.268kg$ (Weight of oven-dried product)
m_w = 73.20%

Therefore, the moisture content in 5kg of moringa leaves is given as:

$$m_{5kg} = 3.66kg.$$

Final or Equilibrium Relative Humidity: If we consider an adiabatic drying process, and assuming that the air remains in contact with the material for a long time, then it will attain a condition such as the partial pressure of the vapour in the air equals the partial pressure of the vapour in the material. When this occurs, for that temperature, no further drying of the material by air takes place.
Therefore, the final or equilibrium relative humidity is calculated using Sorption Isotherms equation given by Hernandez et.al (2000) as follows:
$a_w = 1 - Exp[-Exp(0.914 + 0.5639 lnM)]$….. (2)
Where,
$M = m_d/(100 - m_d)$
$\varphi_{eq} = a_w$ x 100 …..……………………... (3)
The equilibrium Relative Humidity is determined using equation (2) and (3);

$$a_w = 1 - Exp[-Exp(0.914 + 0.639 lnM)]$$

$$Where,$$

$M = \frac{\boldsymbol{m_d}}{\boldsymbol{100 - m_d}}$; $m_d = 9$
$M = 0.0989,$

$$\varphi_{eq} = 49.17\%$$

Quantity of heat needed to evaporate moisture: The drying of any material involves migration of water from the interior of the material to its surface, followed by the removal of the water from the surface. The rate of movement differs from one substance to another. These differences are greatest between hygroscopic and non-hygroscopic materials. For non-hygroscopic materials, drying can be carried out to zero moisture content. For the hygroscopic material, such as moringa will have residual moisture content. There is then equilibrium between the vapour pressure of the air and that of the material being dried, and the drying rate becomes zero. It may be necessary to reduce the rate of drying to prevent cracking of the surface. In most drying operations, the heat comes from the air itself, which is cooled by evaporation: this relationship (latent heat for evaporation given up by air) can be expressed by the following (Milan and Stakic, 2000):

$E = m_w h_{fg} = m_a c_p (T_2 - T_1)$ ……... (4)
The heat supply for drying in the system is given by:
$E_{dry} = E_s + E_e \partial_{ES} - Q_L$………….. (5a)
$\dot{E}_{dry} = \eta_c G A_c t_d + I^2 R t_d - Q_L$…… (5b)
Where,
$E_s = \eta_c G A_c t_d,$
$E_s = I^2 R t_d,$

$$\partial_{ES}(T < 60°\mathrm{C}) = 1,$$
$$\partial_{ES}(T > 60°\mathrm{C}) = 0,$$

The latent heat of vaporization can also be calculated by using the equation given by Youcef-Ali et.al, (2000) as follows:
$h_{fg} = 4.186 * 10^3 (597 - 0.56 T_{pr})$ …. (6)

Where,
$T_{pr} = 60°\mathrm{C}$(Product temperature in drying cabinet).
h_{fg} = 2358.39 k J/kg ,
From equation (4),

E = 8631.71 kJ.

The total heat energy, E (kJ) required to evaporate the moisture can also be calculated from:
$E = \dot{m}_a(h_f - h_i)t_d$ ………………... (7)

The specific enthalpy (h) of moist air at ambient relative humidity in kJ/kg dry air at T(^{o}C) can be approximated by (Brooker et.al, 1992)
$h = 1.006.9T + w[2512.131 + 1.5524T]$... (8a)

Where,
The absolute humidity, w (kg/kg) can be calculated using the expression given by (Eastop, 2000)

$w = \frac{0.622\eta p_{sat\ (T)}}{p - p_{sat}}$……..…………………….(8b)

Average Drying Rate (Rate of Evaporation):
Average drying rate, $\dot{m}_{dr}$ (kg/s) is determined from the mass of moisture to be removed by the heat supply to the system and the drying time by the following equation:
$\dot{m}_{dr} = \frac{m_w}{t_d}$ …………………………………. (9)
Efficiency of Dryer
$\eta_d = \frac{m_w h_{fg}}{G A_c t_d}$,……………….............…… (10)

The mass of air per unit time needed for drying is calculated using equation given by Sodha et.al, (1987) as follows:
$\dot{m}_a = \frac{\dot{m}_{dr}}{[w_f - w_i]}$ ……………………… (11)

From the total heat energy required to evaporate the moisture and the net radiation received by the tilted collector, the drying system collector area A$_c$, in m^2 can be calculated from the equation, since the energy received by the collector is used to dried the moisture,
$A_c G \eta_c t_d = E = \dot{m}_a(h_f - h_i)t_d$……….. (12)

Therefore, the area of the solar collector is given by:
$A_c = \frac{E}{G\eta_c t_d}$ …………………………….. (13)
Where,
η$_c$= collector efficiency, (30% - 50%) (Sodha et.al, 1987)

Volumetric air flow rate, V_a, is obtained by dividing the mass flow rate of the air by the density of the air, i.e;
$\dot{V}_a = \frac{\dot{m}_a}{\rho_a}$ ……………………..,………… (14)

Air Vent Dimension: The air vent area is calculated by dividing volumetric air flow rate by the sum of the wind speed and the velocity of the fan;

$A_v = \frac{\dot{V}_a}{u_w + V_f}$ ………………………………(15)
$L_v = \sqrt{A_v}$ …………………….……. (16)

Rate of Heat Loss from the Dryer: Consider the situation whereby the air is in contact with the surface of the dryer of length, L, and width, w, then the heat loss, Q$_{L,}$ is calculated using the expression given by (Rapjut, 2008),
$\dot{Q}_L = hA(T_e - T_1)$ …………………………………………… (17)
The average heat transfer coefficient, h, is determine from the Nusselt numbers, which is given in Rajput (2008), for the turbulent regime as:
$Nu_L = \frac{hL}{k} = 0.036\, Re_L{}^{0.8} Pr^{\frac{1}{3}}$…………………….. (18)

$Eqn(18) isvalidforPr > 0.5$

$Re_L = \frac{\rho U_w L}{\mu} = \frac{U_w L}{v}$ …………………………………………… (19)

$Pr = \frac{\mu C_p}{k}$ ……………..……………………………………….……... (20)

The properties of the air is determined at mean bulk temperature, $T_b = \frac{T_e + T_a}{2}$.

In Convection heat transfer problems, we write for the functional dependence of the heat transfer coefficient for flow over a flat plate as:

$Nu = \frac{hl}{k} = f(Re, \mathrm{Pr})$,………………………………………(21)

In convection mass-transfer problems, Holman (2000) expressed the functional relation as

$Sh = \frac{h_{cc} l}{D_c} = g(Re, Sc)$, …………………………………… (22)

Also, for laminar flow, Holman (2000), also showed that the functions

$Nu = f(Re, \mathrm{Pr})$,

$Sh = g(Re, \mathrm{Pr})$are identical. This is also true for turbulent flow.

For turbulent flow across a flat plate, one finds, (Rajput, 2008)

$Nu = 0.036 Re^{0.8} Pr^{1/3}$ ………..………………. (23a)

Therefore,

$Sh = 0.036 Re^{0.8} Sc^{1/3}$ ………………………… (23b)

$Sc = \frac{v}{D_c}$ …………………………………………….…... (24)

Shirmer's equation gives:

$D_c = 2.26X10^{-5} \frac{1}{P} (\frac{T}{273})^{1.81}$ …………………...(25)

$h_{cc} = \frac{h}{\rho C_p}$ ……………………………….………………(26)

The rate of evaporation,$d\dot{m}$, kg/s can also be calculated using the expression given by

$d\dot{m} = h_{cc}(C_w - C_o) dS$, ……………………….... (27)

$C_w = \frac{p_{sat}(T)}{r_w T_w}$ …………..……………………………… (28)

$C_o = \frac{P_v}{r_a T_a}$ ……………………………………………... (29a)

$P_v = \eta p_{sat}(T_a)$ …………………………………….. (29b)

Table 3.1: Average air properties measured experimentally

S/No	DESCRIPTION	AVERAGE VALUE
	Relative Humidity, η (obtained experimentally)	63.4%
2.	Solar Radiation, G	418 W/m^2
3.	Ambient Air Temperature, T$_1$	30^{O}C
4.	Wind Speed, U$_w$	2m/s
5.	Time for Drying, t$_d$ (given)	2 days (23 hours, 11.5hrs per day of sunshine =82800sec)
6.	Collector's Efficiency, η$_c$,(given) (worse case)	30%
7.	Fan Velocity, V$_f$ (measured)	5.0m/s

C$_p$ = 1.0069kJ/kg (specific heat capacity of air at ambient temperature),

ΔT = 60^{o}C. (Allowable temperature in the drying cabinet).

The moisture content analyzed and the average air properties are summarized in table 3.2.

Table 3.2: Data used for design (Measured Values)

S/No	Description	Average Value
1	Relative Humidity, η (Obtained experimentally)	63.4 $\pm$1.0%
2.	Solar Radiation, G	418$\pm$0.1 W/m^2
3.	Air temperature	30 $\pm$1.0^{o}C
4.	Wind speed	2.0 $\pm$0.1 m /s
5.	Moisture content of 5 kg of moringa	3.66 $\pm$0.01kg

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Note: the prevailing direction of wind measured in Sabon Gari, Kano, Nigeria, was south-west (SW).
However, these average values shown in the table 3.2 were used in the design calculation and the summary is shown in table 3.2 given below:

Table 3.3: Design calculation summary

`S/No.	Description	Values obtained
1.	Product temperature, T_{pr}	60±1.0 ºC
2.	Moisture content for 5 kg of moringa, m_w	3.66 ±0.01 kg
3.	Energy required to evaporate the moisture, E	8631.71±27.0 Kj
4.	Energy supplied from the collector to dry the product	11467.468±104.0kJ (1.1467x10^4 ± 104.0 kJ)
5.	Rate of evaporation (direct) $\dot{m}_{dr}$	4.42x10^{-5} ±1.2x10^{-7} kg/s.
6.	Rate of evaporation using formular, $\dot{m}_{dr}$	1.245x10^{-4}kg/s
7.	Area of collector, A_c	1.1023 ±0.04m^2
8.	Length of collector, L_c	1.05±0.02m
9.	Area of the dryer, A_d	1.464±0.08m^2
10	Length of the dryer, L_d	1.211±0.3m
11.	Equilibrium or final Relative humidity	49.17±1.0%
12.	Area of Air vent, A_v	6.786x10^{-4}±$6.0x10^{-5}m^2$
13.	Length of air vent, L_V	0.010±0.008m
14.	Dryer efficiency,η_d	22.57±1.0%
15.	Calculated time for drying	2.51±0.02 days

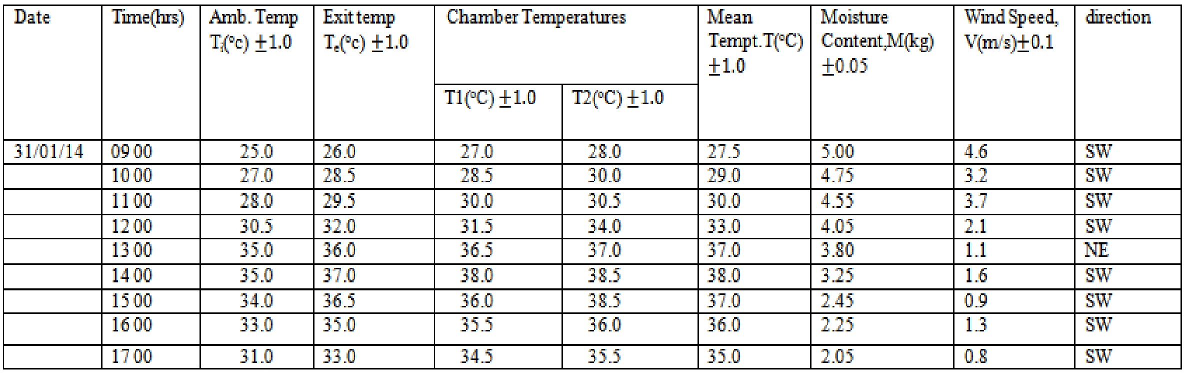
3.2.3 Test Procedure

Cabinet solar drying and open-air drying experiments were carried out for Moringa Oliefera leaves simultaneously. 5kg of Moringa was measured as a sample and spread on the Teflon net of drying cabinet of the dryer and another 5kg was also measured and sun- dried at ambient temperature. To increase the air circulation rates, wind- operated ventilator (fan) placed in the Chimney is switched on.

As the drying process continued, the Moringa leaves inside the dryer were turned over and over using the handle attached to the dryer for even circulation of air in the dryer from time to time. During the experiment, ambient temperature, relative humidity and wind velocity, inlet and outlet temperatures of the dryer, temperature inside the chamber and the temperature of the chimney are recorded on hourly basis from 9.00 am to 5.00 pm. Also, the weight of the Moringa leaves inside the dryer and outside the dryer was weighed on hourly basis to notice the change in moisture content until the product acquired constant weight, that is, equilibrium moisture content. The experiment lasted for three (3) days, from 31/01/2014 to 02/01/2014.

The experimental results for the solar dryer and open air drying were collected and tabulated as shown in table 3.8 – 3.9 and table 4.1 below

Table 3.8a: Experimental Data for mixed-mode solar dryer for 31/01/2014.



Date	Time(hrs)	Amb. Temp T_i(°c) ±1.0	Exit temp T_e(°c) ±1.0	Chamber Temperatures		Mean Tempt. T(°C) ±1.0	Moisture Content, M(kg) ±0.05	Wind Speed, V(m/s)±0.1	direction
				T1(°C) ±1.0	T2(°C) ±1.0				
31/01/14	09 00	25.0	26.0	27.0	28.0	27.5	5.00	4.6	SW
	10 00	27.0	28.5	28.5	30.0	29.0	4.75	3.2	SW
	11 00	28.0	29.5	30.0	30.5	30.0	4.55	3.7	SW
	12 00	30.5	32.0	31.5	34.0	33.0	4.05	2.1	SW
	13 00	35.0	36.0	36.5	37.0	37.0	3.80	1.1	NE
	14 00	35.0	37.0	38.0	38.5	38.0	3.25	1.6	SW
	15 00	34.0	36.5	36.0	38.5	37.0	2.45	0.9	SW
	16 00	33.0	35.0	35.5	36.0	36.0	2.25	1.3	SW
	17 00	31.0	33.0	34.5	35.5	35.0	2.05	0.8	SW

Table 3.8b: Experimental Data for mixed-mode solar dryer for 01/02/2014.

Date	Time(hrs)	Amb. Temp T_i(°c) ±1.0	Exit temp T_e(°c) ±1.0	Chamber Temperatures		Mean Tempt. T(°C) ±1.0	Moisture Content, M(kg)±0.05	Wind Speed, V(m/s) ±0.1	direction
				T1(°C) ±1.0	T2(°C) ±1.0				
01/02/14	09 00	26.0	27.0	27.5	28.5	28.0	1.95	3.2	SW
	10 00	27.0	28.0	29.5	30.0	30.0	1.80	2.2	SW
	11 00	30.0	32.0	33.0	34.5	34.0	1.70	1.2	SW
	12 00	35.0	36.5	37.0	39.0	38.0	1.65	4.2	SW
	13 00	33.0	37.0	38.5	41.0	40.0	1.55	2.6	SW
	14 00	31.5	35.0	36.5	39.0	38.0	1.40	1.1	SW
	15 00	30.0	31.0	35.0	37.5	36.0	1.25	0.8	SW
	16 00	29.0	31.5	32.0	34.0	33.0	1.05	1.0	SW
	17 00	31.0	33.0	34.5	35.5	35.0	0.90	0.7	SW

Table 3.8c: Experimental Data for mixed-mode solar dryer for 02/02/2014.

Date	Time(hrs)	Amb. Temp T_i(°c) ±1.0	Exit temp T_e(°c) ±1.0	Chamber Temperatures		Mean Tempt. T(°C) ±1.0	Content, M(kg)±0.05	Wind Speed, V(m/s) ±0.1	direction
				T1(°C)±1.0	T2(°C) ±1.0				
02/01/14	09 00	25.0	26.0	26.5	27.0	27.0	0.85	3.6	SW
	10 00	27.0	28.0	29.5	30.0	30.0	0.80	2.9	SW
	11 00	29.5	31.0	32.0	33.0	32.5	0.80	1.7	SW
	12 00	31.0	33.5	34.0	35.5	35.0	0.80	1.1	SW

Table 3.9a: Temperatures and Relative Humidity for solar dryer on 31/01/15

Outside the dryer (Ambient Air)						Inside the Dryer			
Date	Time(hrs)	T_d (°c) ±1.0	T_w(°c) ±1.0	Depr. (°c)	Rel.Hum. (%)	T_d (°c) ±1.0	T_w (°c) ±1.0	Depr. (°c)	Rel.Hum. (%)
31/01/14	09 00	25.0	22.0	2.0	84.0	27.0	24.0	3.0	77.0
	10 00	27.0	24.0	3.0	77.0	28.0	26.0	2.0	85.0
	11 00	28.0	25.0	3.0	77.0	30.0	26.0	4.0	72.0
	12 00	30.5	25.0	4.5	68.5	31.5	27.0	4.5	69.5
	13 00	35.0	26.0	8.0	52.0	36.5	28.0	8.5	50.5
	14 00	35.0	26.0	9.0	47.0	38.0	29.0	9.0	50.0
	15 00	34.0	28.0	9.0	46.0	36.0	27.0	9.0	48.0
	16 00	33.0	26.0	7.0	55.5	35.5	27.0	8.5	49.5
	17 00	31.0	26.5	7.0	55.0	34.5	26.0	9.5	43.5

Table 3.9b: Temperatures and Relative Humidity for solar dryer on 01/02/15

Outside the dryer (Ambient Air)						Inside the Dryer			
Date	Time(hrs)	T_d (°c) ±1.0	T_w(°c) ±1.0	Depr. (°c)	Rel.Hum. (%)	T_d (°c) ±1.0	T_w (°c) ±1.0	Depr. (°c)	Rel.Hum. (%)
01/02/14	09 00	26.0	22.0	4.0	69.0	27.5	18.0	9.5	35.5
	10 00	27.0	22.5	4.5	66.0	29.5	20.0	9.5	45.5
	11 00	30.0	23.5	6.5	56.0	33.0	24.0	9.0	45.0
	12 00	35.0	24.0	11.0	37.5	37.0	25.0	12.0	35.0
	13 00	33.0	23.0	10.0	40.0	39.0	26.0	13.0	33.0
	14 00	31.5	22.0	8.5	45.5	37.0	25.0	12.0	35.0
	15 00	30.0	20.5	9.5	39.0	35.0	23.0	12.0	33.0
	16 00	29.0	20.0	9.0	40.5	32.0	22.0	10.0	39.0
	17 00	28.0	19.0	9.0	39.0	30.5	20.5	10.0	37.0

Table 3.9c: Temperatures and Relative Humidity for solar dryer on 02/02/15

Outside the dryer (Ambient Air)						Inside the Dryer			
Date	Time(hrs)	T_d (°c) ±1.0	T_w(°c) ±1.0	Depr. (°c)	Rel.Hum. (%)	T_d (°c) ±1.0	T_w (°c) ±1.0	Depr. (°c)	Rel.Hum. (%)
02/02/14	09 00	25.0	18.0	7.0	47.0	26.5	19.0	7.5	46.0
	10 00	27.0	19.0	8.0	44.0	29.5	20.0	9.5	38.0
	11 00	29.5	20.0	9.5	38.0	32.0	21.0	11.0	34.0
	12 00	31.0	21.0	10.0	37.5	34.0	22.0	12.0	32.0

Table 4.1: Moisture Content of an Open Air drying of Moringa

Date	Days	Mass (kg)
31/01/14	1	5.0
01/02/14	2	3.30
02/02/14	3	1.35
03/02/14	4	1.25
04/02/14	5	1.25

IV. RESULTS AND DISCUSSION

Hourly variations of temperature, wind velocity and relative humidity were recorded for three days in solar dryer and the mean is given in table 3.8a, 3.8b, 3.8c, 3.9a, 3.9b and 3.9c. From the observation, it is found that the temperature outlet of the collector and temperature inside the drying chamber are much higher than the ambient temperature. This indicates that the performance of solar dryer is better than the performance of the open-air drying due to the fast migration of moisture as a result of the present of heat inside the dryer.

From the table, it can be seen that the average highest temperature recorded for the solar mix-mode cabinet dryer is 40℃ and the minimum temperature is 27℃. The mass of the Moringa also reduced from 5kg to 0.8kg in the solar dryer during the drying process. However, the highest and lowest relative humidity in the dryer as shown in table 3.9 (a-c) was 85% and 32% respectively. This occurs in the first and last day of the drying respectively. Table 3.8 (a-c) also shows the high presence of wind during the drying with the highest wind speed being 4.6m/s recorded during the first day of drying. This must be one of the reasons why the drying time was reduced.

Variation of average temperature with respect to time of the day is shown in figure 4.2. It is found that the average temperature is higher at 1 p.m of the day. The maximum and minimum temperature recorded during these days inside the dryer are 40℃ and 27℃ respectively.

4.1 Performance Evaluation of Solar Drying System

Solar drying performance was compared between ambient temperatures for the period of experimentation. The performance of the solar dryer

was highly dependable as it takes 20 hours to dry 5 kg of Moringa whereas, it takes 96 hours (4 days) to dry the same 5kg at open-air (ambient temperature). Figure 4.2 (a-c) shows the variation of average temperature inside the dryer for the 3 days the test lasted. Highest temperature of 40℃ was recorded inside the dryer.

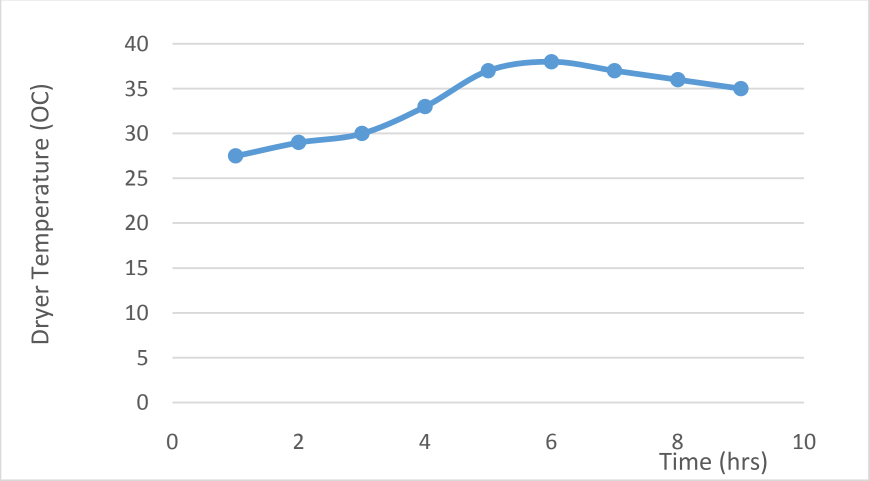


Figure 4.2a: Variation of Dryer Temperatures with time for 31/01/14.

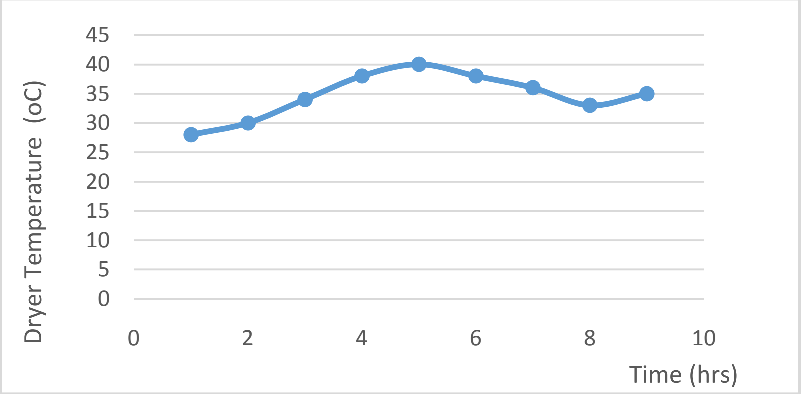


Figure 4.2b: Variation of Dryer Temperatures with time for 01/02/14.

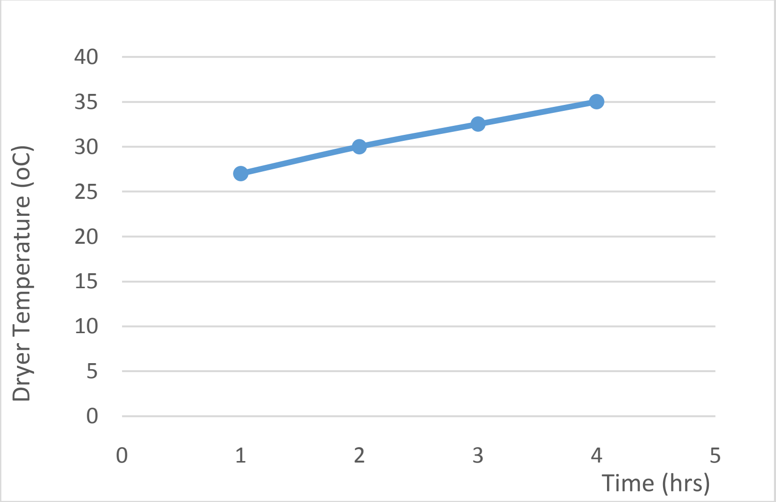


Figure 4.2c: Variation of Dryer Temperatures with time for 02/02/14.

Variation of moisture content with drying time for solar drying and open-air drying is shown in Figure 4.3 (a-b). The time taken by the solar dryer to reduce the moisture content of Moringa from 73.2% to 9.0% is 20 hours as compared to 96 hours (4 days) in open-air or natural sun drying.

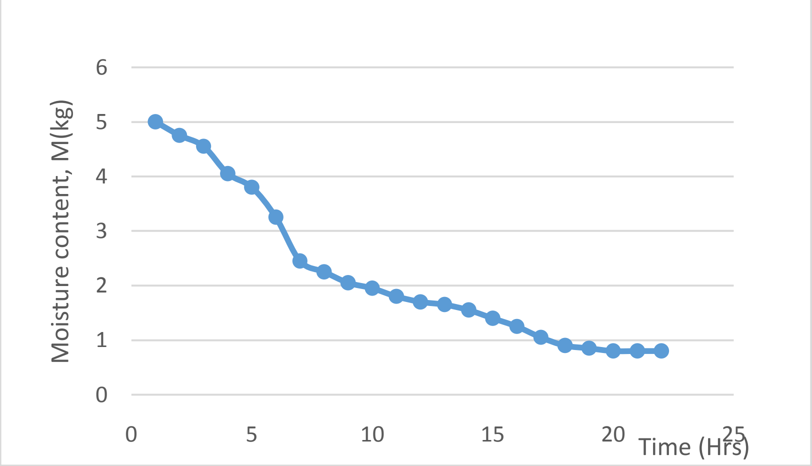


Figure 4.3a: Variation of moisture content of Moringa with time (solar dryer)

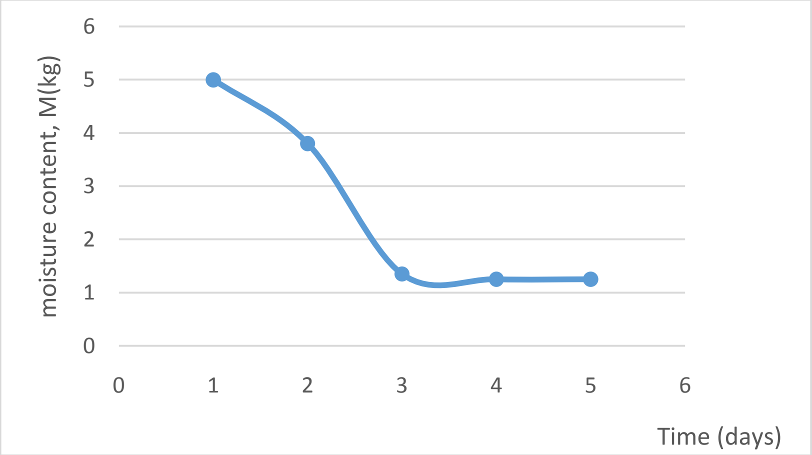


Figure4.3b: Variation of moisture content of Moringa with time (Open-air drying).

Figure 4.3 above also shows that much water was remove from the Moringa dried using the solar dryer as the 5kg Moringa was reduced to 0.8kg compared with that of open air drying in which 5kg Moringa was reduced to 1.25kg.

Variation of relative humidity with drying time of solar dryer is shown in figure 4.4 (a-c), the relative humidity is higher in the first day, about 85% and 32% on the last day respectively.

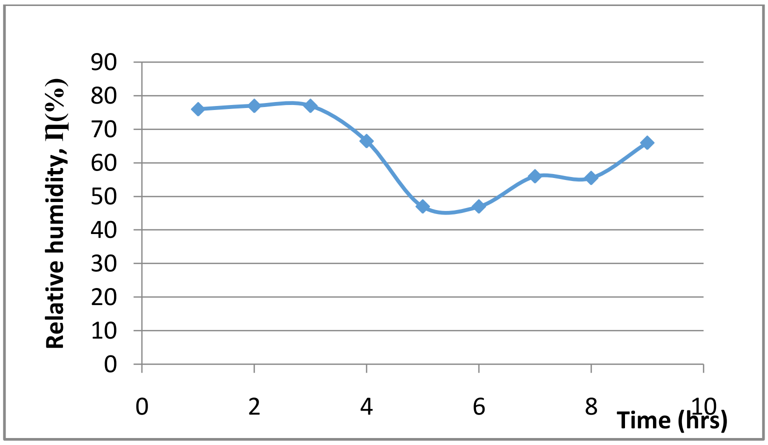


Figure 4.3a: Variation of dryer Relative humidity withTime (31/01/15).

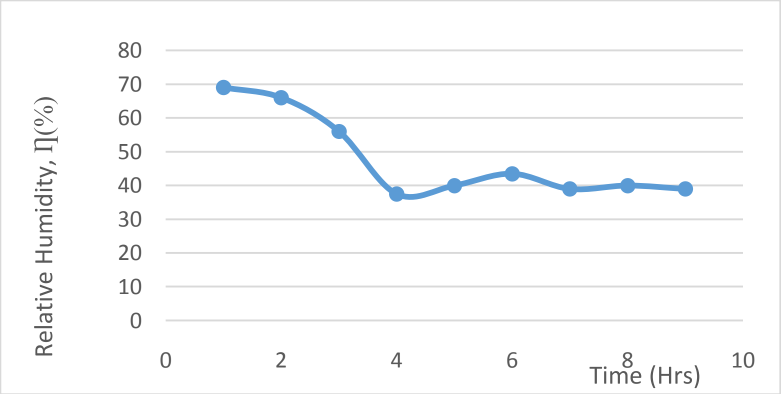


Figure 4.3b: Variation of dryer Relative humidity with time (01/02/14).

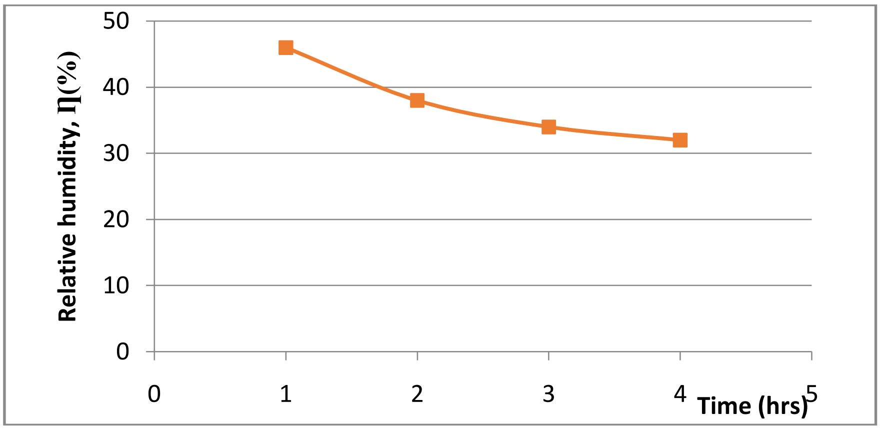


Figure 4.3c: Variation of dryer Relative humidity with Time (02/02/14).

V. CONCLUSION

The constructed dryer used in the present research work reduces the drying period of the Moringa leaves considerably. The minimum drying period of 20 hours was achieved for 5kg Moringa leaves to attain equilibrium in solar dryer, whereas the time taken by open-air drying was 96 hours (4 days). The dryer can be used to dry other products that cannot be dried in natural sun drying since the dryer would not expose the products to direct sun light. This solar dryer also offers an additional advantages; ease of construction, low maintenance and protection of the crop from weather, thus minimizing damage from inclement rains.

Depending on the time and weather conditions, the drying cabinet was able to attain a mean hourly temperature of the range 27°Cto 40°C.

REFERNCES

[1]. Anwar F., S. Latif, M. Ashrat and A.H. Gilani, (2007). Moringa oleifera: A food plant with multiple medicinal uses. Phytother. Res., 21: 17-25.

[2]. Baker, Christopher G.J, (1997), “Industrial drying of foods”,Blackie Academic & professional, London.

[3]. Brooker, B.D; Baker Arkema., Drying of Cereal Grains. The AIV Publishing Company Inc., West port, Connecticut, 1975

[4]. David E. and Whitfield V.,Solar Dryer Systems and the Internet: importantresources to improve food preparation; INTERNATIONAL CONFERENCE ON SOLAR COOKING, 26TH - 29TH NOVEMBER, 2000.

[5]. Eastop.T.D and McConkey.A, (2002), Applied Thermodynamics for Engineering technologiest, Published by Pearson Education (Singapore) Pte. Ltd., Indian branch

[6]. El Paso Solar Energy Association: http://www.epsea.org/dry.html

[7]. Fuglie L.J., (1999). Moringa: Natural Nutrition for the Tropics. Dakar: Church

[8]. Holman .J.P, Mass Transfer (Heat Transfer), Tata McGraw-Hill publishing Company Limited,2002.

[9]. Kerr and Barbara: A REVIEW OF SOLAR FOOD DRYING; (1999) - Kerr, Barbara. The Sustainable Living Center. 3310 Paper Mill Road, Taylor, Arizona 85939 USA. Schematic of downdraft design. e-mail: kerrcole@frontiernet.net

[10]. Laws N., Mathematical Modelling of Heat and Mass Transfer in Agric. Grain Drying. Proc. R. Society, London, 1973.

[11]. Madhlopa .A; Jones S. A and Kalenga Saka J.D (2002), a solar air heater with composite absorber system for food dehydration. Renewable energy 27: 27-37

[12]. Morimitsu, Y.; K. Hayashi, Y. Nakagawa, F. Horio, K. Uchida and T. Osawa,(2000). Antiplatelet and anticancer isothiocyanates in Japanese domestic horseradish, wasabi. Biofactors, 13: 271-276.

[13]. Norton F.H, Drying Theory, Cranfield Institute of Technology, Bedford, England, June 1985 (Unpublished)

[14]. Peter K.V., (2008). Underutilized and Underexploited Horticultural Crops:,

[15]. Rajput R.K, Heat and mass transfer, S. Chand and company Ltd, 2008.

[16]. Rauf .O. O, Utilization of green-house effect for solar drying of corn, 2000.

[17]. Scanlin and Dennis: The Design, Construction and use of an Indirect, Through-Pass, Solar Food Dryer; extracted from Home Power magazine, Issue No. 57, Feb/March 1997. Pages 62 - 72. Email:scanlindm@appstate.edu

[18]. Sodha M.S., Bansal N.K., Kumar A., Bansal P. K, Malik M.A.,Solar Crop Drying, Vol. I and II. CPR press, Boca Raton, Florida, 1987.

[19]. Verma, S.C.; R. Bannerji, G. Mirra and S.K. Nigam, 1976. Nutritional value of Moringa. Curr. Sci., 45: 769-770. 2459

[20]. "USDA GRIN Taxonomy". http://www.ars-grin.gov/cgi- bin/npgs/html/taxon.pl World Service Volume 4. New India Publishing. pp. 112. ISBN 81-89422-90-1.http://books.google.com/books?id=lPozmrZcC&lpg=PA111&dq=moringa%20oleifera&pg=PA112#v=onepage&q&f=false.

emmanuel, O. A"Design, Construction And Testing Of A Moringa Oliefera Mixed-Mode Cabinet Solar Dryer.“American Journal of Engineering Research (AJER), vol. 7, no. 07, 2018, pp. 11-25.