# A comparison of the drying kinetics, energy consumption and colour quality of drying medicinal leaves in direct-solar dryer with different colours of collector cover

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## Abstract

In some countries, Neem and Bitter leaves are often offered as dried medicinal leaves and one of the appealing aspects to consumers is that they retain their original colour after drying. Hence, the purpose of this study was to examine if collector cover colour variations can impact the quality and chlorophyll loss in solar-dried Neem and bitter leaves. To vary the colour spectrum, three distinct coloured polyethene materials with different colours were used as top window-cover for the dryer chamber and collector, which formed a single drying unit of a solar cabinet dryer. The results showed that the yellow-covered solar drying unit achieved 38.8% thermal efficiency, which declined by 1.43% and 10.41% for the blue and white-covered drying unit respectively. The yellow-cover dryer created higher internal temperature and drying rate, enabling it to dry the leaves faster. The average drying rate for Neem and bitter leaves was 0.003762-0.003849kg/h, and 0.004348-0.004689 kg/h respectively. The specific energy consumption for drying the leaves ranged from 10.52-13.89 MJ/kg for all dryers. Colour analysis showed that the yellow-covered dryer dried bitter leaf near its natural colour, while the blue-covered dryer dried Neem near its natural colour. Lograthimic model predicted their moisture ratio better for drying the leaves.

**Keywords:** solar collector; green leaves; chlorophyll; drying; colour wavelength

Nomenclature

| | | | |
|---|---|---|---|
| A | Collector Area (m2) | | Subscripts |
| Cp | Specific heat (J/kg.K) | a | air or ambient |
| Deff | Effective diffusivity (m2/s) | i | initial or inlet |
| FR | Heat removal factor (-) | d or dr | Drying or dried |
| IT | Total solar radiation incident on the solar collector (W/m2) | c or o | collector |
| $L_v$ | Latent heat of vaporization of water (J/kg) | w | water |
| m | Mass (kg) | | |
| M | Moisture content (kg of water/kg wet solids) | T | Thermal storage |
| Mdr | Drying rate (kg of water/kg of dry solid/h) | u | utilized |
| Q | Total energy (W) | | |

| | | | |
|---|---|---|---|
| | | Greek letters | |
| t | Total drying time (h) | ɳ | Efficiency (%) |
| $T$ | Temperature (°C) | $\alpha$ | Absorbance (-) |
| $U_o$ | heat loss coefficient (W/m2 oC) | $\dot{m}$ | Mass flow rate (kg/s) |
| w | Total weight of leaves to be dried per batch(kg) | $\tau$ | Transmittance (-) |
| | Abbreviations | | |
| BCC | Blue colour window covered solar dryer | | |
| WCC | White colour window covered solar dryer | | |
| YCC | Yellow colour window covered solar dryer | | |

## 1. Introduction

In Africa, a lot of green leaves are used as medicine (Ndukwu et al, 2018; Ejike and Ndukwu, 2017). Among these leaves are Neem leave (*Azadirachta indica*) and bitter leaves (*Vernonia Amygdalyna*). To process these leaves for secondary uses in medicine, and food for ease of packaging and transportation, these leaves are dried, milled and packaged for further uses. Drying which is a simultaneous heat and mass transfer process involves the use of thermal energy to reduce the moisture content available in the agricultural product (Ndukwu et al., 2017, Ertekin and Yaldiz, 2004). Additionally, reducing the moisture content increases the shelf life of the leaves as microbial activities are limited within the intermolecular structure of the agricultural product (Azaizia *et al.,* 2017 Fakayode 2013). This is usually a concern due to the perishable state of agricultural products. To keep the original constituent of herbs, it should be dried immediately after harvest (Jin et al., 2018). In most developing countries, open sun drying is mostly used in drying medicinal leaves. However, open sun drying has numerous disadvantages which affect product quality and the farmer's net profit (Eke 2013, Chen *et al.,* 2007 and Alonge *et al.,* 2007). This includes pest infestation, attack by rodents, the introduction of contaminants, attack by birds, dispersal by wind, reduction in aesthetic value and many other problems were associated with open-air drying. There is also a problem of lower drying rate and uncontrollable heat transfer to the product (Lakshmi et al., 2019). This and many more led to the development of other drying methods other than open-air drying. The various energy sources used in drying includes biomass, electrical, fossil fuel, geothermal, solar, wind etc. However, among theses energy sources, renewable energy sources like wind, biomass, solar etc has been found to be clean and environmentally friendly (Alonge *et al.,* 2012).

Solar energy is well distributed all over the word and is easy to harness for thermal applications. Therefore it has been applied in the drying of agricultural products. It exhibits faster drying rates than open sun drying methods as the heat produced by solar radiation is harnessed with the help of a collector, yielding higher fluid temperatures, lower humidity, higher airflow movement and are eco-friendly (Ndukwu et al., 2020 a). Therefore several solar dryers have been developed and used to dry different crops. Stevia leaves were dried in a time range of 4 to 10 hours using an indirect and direct solar dryer (Tellez et al 2018). Hawa et al (2021) took 18 h to dry pre-treated Cabaya fruits to a moisture content of 9 % in an indirect solar dryer with forced air convection. César et al (2020) took 26 h to dry tomato slices in a mix –mode solar dryer. Other similar crops that have been dried with different design of solar dryer includes mints (Keavan and Arjunan 2018), bitter guard (Arun and Jayaraj 2021), ginger (Sekhar et al 2021), plantain chips (Ndukwu et al (2020 a), tomato pomaces, (Milczarek et al 2017), pepper and grapes (ELkhadraoui et al 2015), tomato (Kesavan, et al., 2019; Azam et al., 2020), banana (Amer et al., 2010), Cashew nut (Dhanushkodi et al., 2014), Apples (Wang et al., 2018), watermelon (Lingayat et al., 2020), black turmeric (Lakshmi et al., 2018) etc. However, solar dryers are classified based on design or mode of operation as direct solar dryers, indirect solar dryers, hybrid, mixed mode, natural and forced convection solar dryers (Kumar *et al.,* 2016). Therefore different configurations of solar dryers have been developed in the literature. Ashfri et al (2021) developed a compact indirect solar dryer for drying sludge while

Lingayet et al (2017) developed an indirect solar dryer for drying banana slices. Madhankumer et al (2021) in their design of an indirect solar dryer incorporated a fin inserted in a phase change material while Dutta et al (2021) developed a solar dryer with a corrugated collector for drying medicinal plants. However, in most African countries, direct cabinet solar dryers with natural convection are prevalent due to ease of fabrication and low cost (Ndukwu et al, 2018). Previous studies have shown the performance of different designs of direct solar dryers with different amounts of energy received by the drying product (Kumar et al, 2016, Prakash et al. 2016). To capture solar radiation through the so-called "greenhouse effect," a collector's absorber must be covered. A cover should have maximum solar radiation transmissivity and should be waterproof. The absorber plate's released long-wave radiation must be opaque to the glazing cover (Bansel and Sharma, 1986). The required cover characteristics are transmissivity, reflectivity, and absorptivity which depend on incoming radiation, cover thickness, refractive index, and material extinction coefficient (Bansel and Sharma, 1986). Furthermore, the cover should be inexpensive, strong, abrasion-resistant and weather resistant. It is generally known that different colour bodies absorb and transmits light differently. Transparent glazing materials especially glass material identified with white colour absorb 13% of the heat from sunlight and allow approximately 70% of sunlight energy to pass through it (Zhao et al., 2022). Therefore, varying the cover colour means varying the wavelength and transmittance when considering the colour spectrum. Red and blue wavelengths are known to influence plants in photosynthesis and by extension the chlorophyll available on the leaves. While research is ongoing to understand the impact of light wavelength on plant leaves response during photosynthesis and the mechanism associated with it, it's also imperative to study how these light wavelengths can also affect it under thermal conditions (Yavari et al., 2021).

Colour plays a major role in determining the quality of dried leaves and their acceptability (Xie et al., 2014). Appearance is very important in the selection of herbs and it shows how closely they are to the fresh product. In some countries, Neem and Bitter leaves are often offered as dried medicinal leaves and one of the appealing aspects to consumers is that they retain their original colour after drying. Although, solar dryers have been shown to dry leafy agricultural products better than other drying methods in terms of maintaining the nutritional and biochemical properties but chlorophyll leaching still is a major concern. During drying the chlorophyll and the plasma membrane are structurally damaged which affects the carotenoids (Moreira et al., 2015). For most leaves, there is damage in Fucoxanthin embedded in chlorophyll pigments which is photosensitive. Thus different light colour wavelength impact differently on the chlorophyll present in the leave. Additionally, during the drying of leaves, chlorophyll leaching occurs due to heat. In the case of direct solar drying, both heat and photo effect from direct solar radiation affects the chlorophyll loss which also affects the natural colour of the leaves. Although Bansel and Sharmer (1986) have noted that the type of collector cover determines the temperature of the heat transfer fluid but the assertion did not characterize the effect of wavelength variation of the solar radiation that can deplete chlorophyll in green leaves. Hence there is a need to investigate the appropriate glazing colour with suitable transmittance necessary to bring the dried herbs closer to their natural green. Consequently, using multiple glazing colours allows you to evaluate the effects of different glazing colours on a dried product. As a result, the goal of this study is to develop three direct passive solar dryers with blue, yellow, and white coloured polyethene material covering both the collector and the drying chamber that are combined to form a single unit for drying Neem and bitter leave, as well as to investigate the effect of varying covering material colour changes on drying time, drying kinetics (moisture loss, drying rate, etc.), and colour quality of dried Neem and Bitter leaf.

## 2.0 Materials and Method

### 2.1 Description of the solar dryer

Three direct solar dyers of a cabinet design with the collector and drying chamber combined to form a single drying unit were constructed using locally available materials. The dryer frame was made with wood, which is economical and a poor conductor of heat. The drying window is rectangular measuring

0.4m by 0.45 m. The entire dryer window was covered with low density 0.4m x 0.45m x 200µm transparent polythene covering of white colour (WCC), blue colour (BCC) and yellow colours (YCC) with a wavelength in the range of 450-590nm and transmittance of about 85-95 %. The choice of different colours of the window cover is to vary the light wavelength with the white colour acting as the control. The drying chamber unit which is 0.4m long, 0.45m wide and 0.6m deep was made from well-seasoned wood. Two drying trays of 0.30m x 0.35m each is placed horizontally inside the drying chamber and were vertically separated at a distance of 0.12 m from each other. The trays are made of a wooden frame and a net where products are placed for drying. A 0.28m x 0.24m wooden door is hinged at the back of the drying chamber which provides means for opening and closing the drying chamber for loading and offloading the agricultural products. At the bottom of the drying chamber unit is fitted a 0.002 m thick aluminium plate which is painted black that served as the absorber. Also 2.8kg of black pebbles were also loaded at the bottom part of the drying chamber to serve as sensible heat storage material to serve as supplementary heat source. However, because air becomes lighter when it absorbs heat and goes upwards due to lower density, the collector plate was positioned beneath the drying tray. The collector receives heat from solar radiation and exchanges it with intake air that flows through an air inlet (0.0015m$^3$) positioned behind the collector and towards the bottom of the solar dryer. Consequently, the inlet air temperature increase which lowers the density of the air, thus it circulates vertically upwards towards the drying trays, where it comes in contact with the leaves, extracting moisture. The circulating hot air leaves the drying chamber through a 0.08m x 0.15m chimney provided at the top front end of the drying chamber. The combined collector and drying chamber unit is inclined in the direction of wind flow and is tilted with a slope of 15.47$^o$ southward. Figure 1 shows the direct solar cabinet dryers which comprise the collector, drying chamber, drying trays, and pebbles for thermal storage. The dimensions of the solar dryer are presented in Table 1.

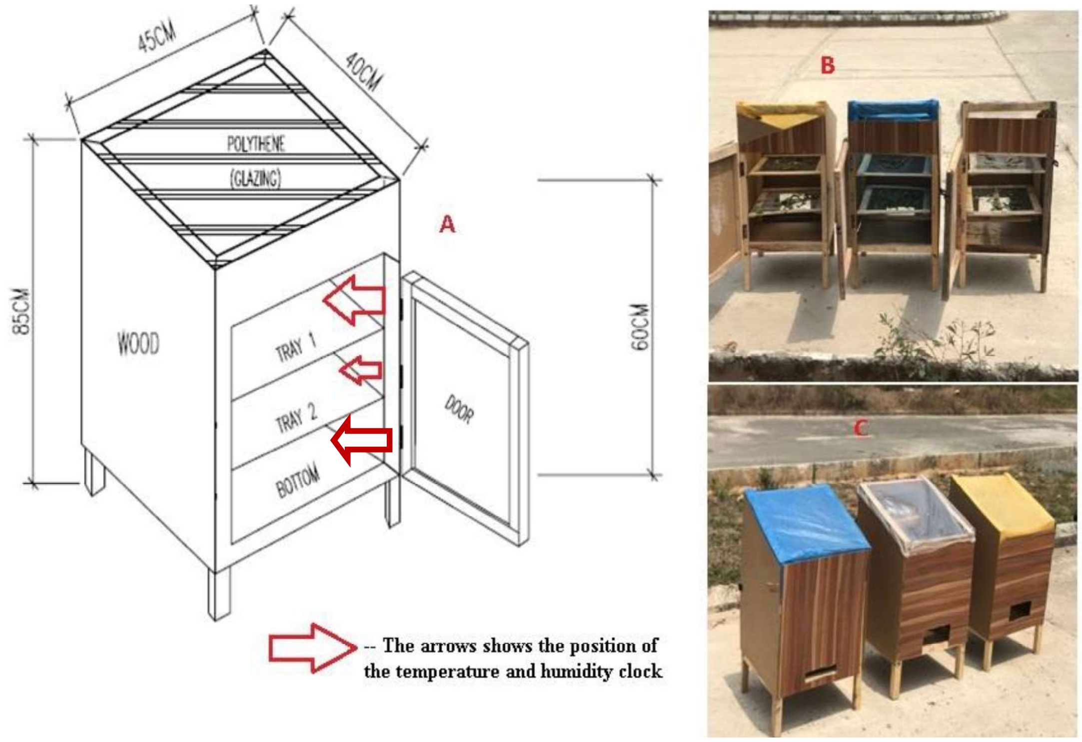


Figure 1: The solar dryers (A) schematics of the solar dryer (B) solar dryer showing the drying trays (C) solar dryer showing the coverings

**Table 1: Component, dimensions, solar dryer parameters**

| Description | Dimension (m) | Unit |
|---|---|---|
| | Length= 0.4 | m |
| Glazing | width =0.45 | m |
| | Thickness=200µm | m |
| | Length=0.4 | m |
| Drying Chamber | width =0.45 | m |
| | Height= 0.6 | m |
| Front view | Length= 0.6 | m |
| | width = 0.45 | m |
| Back view | Length= 0.6 | m |
| | width = 0.45 | m |
| Side view | Length= 0.4 | m |
| Door | Length = 0.28 | m |
| | width = 0.24 | m |
| Area of drying window | 0.18 | $m^2$ |
| Thickness of absorber | 0.002 | m |
| Angle of tilt | 15.47 | $^o$ |
| Number of drying trays | 2 | - |
| Space between trays | 0.22 | m |

## 2.2 Experimental Procedure

### 2.2.1 Sample Preparation

Neem and Bitter leaves were obtained around the local environs in Umudike. The leaves were detached from the stalk and were cleaned to remove all dust. The leaves were identified at the Department of Forestry and Wide Life at the Michael Okpara University of Agriculture Umudike. The leaves were further grouped into three (for the three solar dryer cover colour design) and further subdivided into triplicate (25 g each for Neems and 22g each for bitter leave). The initial moisture content was determined in a dry basis by drying a sample of the leaves at 105°C for 24 h using a laboratory oven (UMB 500 Sehutzart, DIN EN 60529-IP 20). The initial moisture content was determined as follows (Hawa et al., 2020)

$$M_i = \frac{W_i - W_d}{W_i} \quad 1$$

### 2.2.2 Data Collection

The experiment was carried out on January 28$^{th}$ 2023 at Michael Okpara University of Agriculture Umudike Abia State Nigeria on latitude 5.53°N, and longitude 7.49° E. The three solar dryers with blue, yellow and white drying unit covering were set up at the same time with all the appropriate equipment and data collection instruments. The Bitter leaves and Neem leaves were spread to form a single layer on drying trays and allowed to dry to a moisture content of 8.53±0.92 % w.b. Measurement started at the first appearance of a clear sky at 9.00 am and stopped when the sun sets around 6.00 pm local time. Thus drying began at 9 am local time and end at 6 pm local time. The mass of the leaves was manually measured at one-hour intervals until three consecutive constant weights are recorded. However, it was observed that the solar dryers dried the leave to constant weight before 6 pm. The air temperatures and humidity inside the drying unit were measured with a temperature and humidity clock (DTH-82; TLX, Guandong, China). The solar radiation intensity was recorded using a Lutron solar power meter (SPM-1116SD with an accuracy of ±1 $W/m^2$/ day). The weights of the leaves were measured using a weight scale (KERRO model, accuracy of ±0.01 g). The wind direction and velocity were measured using a dual wind vane (AM-4826; Landesk, an accuracy of ±2% of velocity). A Lutron colour analyser (RGB-1002, 45° /0° colour measuring geometry) was used to determine the colour of the dried leaves and HTML colour codes were obtained online. All measurements were made at three points as shown in Figure 1 and the average used in the analysis. Table 2 lists all of the sensitivities, models, and makers of the instruments used in data collection.

Table 2: Specifications and sensitivities of measuring instruments

| Instruments | Measured Parameter | Specifications | Sensitivity | Manufacturer |
|---|---|---|---|---|
| Solar power meter | Solar radiation intensity | SPM-1116SD | ±1 $W/m^2$ | Lutron China |
| Digital balance | Mass | KERRO model | ±0.01 g | KERRO, China |
| Vane Anemometer | Wind speed | AM-4826 | ±2% of velocity). | Landesk, Guangzhou, China. |
| Colour Analyser | RGB colour codes | RGB-1002 | 45° /0° colour measuring geometry | Lutron China |
| Temperature and humidity clock | Temperature and Humidity | DTH-82 | ±0.1 °C, ±1.0 % | TLX, Guandong China |
| Hot air oven | Moisture content | UMB 500 Sehutzart, DIN EN 60529-IP 20 | ± 0.1 ◦C | Memmert, Germany |

### 2.2.3 Colour Analysis

HTML colour codes were generated from the leaves at the beginning and end of the drying process using a Lutron analyzer. Afterwards, the codes were uploaded to an HTML colour server and converted into RGB values. Colour codes in HTML are a computer-readable and displayable format for representing colours. The colour's red, green, and blue components can each be represented by a Hex code, which is a three-byte hexadecimal number (consisting of six variables). There are six alphabets or numbers in every Hex colour code, beginning with the symbol "#". The hexadecimal numeric system is used to represent numbers. There are a total of 1,67,77,216 colour combinations. The code's 00 value range represents the lowest colour intensity, while the FF value range represents the highest. The first and second variables in the Hex colour code represent the intensity of red. The third and fourth variables represent the intensity of green. The fifth and sixth variables represent the intensity of blue. By combining the intensities of red, green, and blue, almost any colour can be created. The white colour is a full-intensity mixture of the three primary colours, with the Hex colour code #FFFFFF representing it.

### 2.2.4 Experimental design

For the drying process, a factorial experimental procedure was applied with

two factors at three and ten levels respectively, laid out in a Randomized complete block design (RCBD) with three replication as shown in Table 3. The first factor, Glazing colour (3 levels), While the second factor, is Temperature (10 levels). The same design was applied to the bitter leave and the Nim tree.

**Table 3: Experimental design**

| Treatment (Glazing Colour) | Temperature t, (°C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (T) | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_6$ | $t_7$ | $t_8$ | $t_9$ | $T_{10}$ |
| $T_1$ | $T_1t_1$ | $T_1t_2$ | $T_1t_3$ | $T_1t_4$ | $T_1t_5$ | $T_1t_6$ | $T_1t_7$ | $T_1t_8$ | $T_1t_9$ | $T_1T_{10}$ |
| $T_2$ | $T_2t_1$ | $T_2t_2$ | $T_2t_3$ | $T_2t_4$ | $T_2t_5$ | $T_2t_6$ | $T_2t_7$ | $T_2t_8$ | $T_2t_9$ | $T_2T_{10}$ |
| $T_3$ | $T_3t_1$ | $T_3t_2$ | $T_3t_3$ | $T_3t_4$ | $T_3t_5$ | $T_3t_6$ | $T_3t_7$ | $T_3t_8$ | $T_3t_9$ | $T_3T_{10}$ |

$T_1$ = Blue colour $T_2$= White colour, $T_3$= yellow colour

### 2.3 Experimental uncertainties

A variety of factors, including reading values, calibration methods, instrument types, and environmental factors, can contribute to uncertainties (Philip et al 2022). The overall uncertainty in experiments can be attributed to both internal and external uncertainties. For very sensitive parameters, especially in solar thermal systems, Philip et al (2022) suggested considering internal uncertainties as well as external uncertainties. The internal and external uncertainties are thus considered in some publications (Kumar et al., 2022). During our evaluation, we measured temperature, relative humidity, solar radiation intensity, and mass. Phillip et al. (2022) estimate the overall external uncertainties as follows:

$$U_{ext} = \sqrt{U_T + U_{rh} + U_{sol} + U_m} \quad 2$$

Where the measured uncertainty for Temperature, relative humidity, solar radiation and, the mass of the product with their reading error is indicated with $U_T$, $U_{rh}$, $U_{sol}$ and, $U_m$ respectively. The uncertainty (Ux) for each measurement is given (Ndukwu et al., 2022b)

$$U_x = \left[\left(\frac{\partial R}{y_1}\right)x_1^{\ 2} + \left(\frac{\partial R}{y_2}\right)x_2^{\ 2} + \cdots + \left(\frac{\partial R}{y_n}\right)x_n^{\ 2}\right]^{1/2} \quad 3$$

$x_1$, $x_2$ and $x_n$ are the experimental uncertainty in the variables $y_1$, $y_2$ and $y_n$.

According to the calculations, the external uncertainties for relative humidity, temperature, solar radiation, and mass are 0.11%, 0.18%, 1.21%, and 0.15%, respectively as shown in Table 4. This resulted in an overall experimental uncertainty of 1.28%. A 0.005% external uncertainty was calculated for moisture contents, a 0.0023% external uncertainty for moisture ratios, and a 0.0042% external uncertainty for energy utilization ratios.

Philip et al. (2022) calculate the experiment's internal uncertainty as follows:

$$U_I = \frac{(\sigma_1^2 + \sigma_2^2 + \cdots \ldots\ldots + \sigma_n^2)}{N} \quad 4$$

The internal uncertainty percentage is provided as follows (Philip et al 2022)

$$\%\ \text{internal uncertainty} = \frac{U_I}{U_{Imean}} \times 100 \quad 5$$

Where $U_I$ denotes the average of all observations. Thus, the proportion of internal errors for temperature, relative humidity, solar radiation, and mass, respectively, was 2.8%, 3.08%, 1.11%, and 0.43%. Thus, the overall experimental uncertainty for temperature, relative humidity, solar radiation, and mass was 2.14%, 2.42%,3.11%, and 1.4%, respectively. After taking into account both internal and external experimental uncertainties, these values fall within the range of total experimental uncertainty described in the literature for agricultural solar drying. For temperature measurement in solar greenhouse dryers, Philip et al (2022) reported an overall experimental uncertainty of 4.98% while Kumar et al (2022) reported an overall experimental uncertainty of 4.12 to 4.36%.

Table: 4 Experimental uncertainties

| Measurement | External uncertainty (%) | Internal uncertainty (%) |
|---|---|---|
| Relative Humidity | 0.11 | 2.42 |
| Temperature, | 0.18 | 2.14 |
| Solar Radiation | 1.21 | 3.11 |
| Mass | 0.15 | 2.14 |
| Moisture Content | 0.005 | 1.01 |
| Moisture Ratio | 0.0023 | 0.76 |
| Energy Utilization Ratio | 0.0042 | 0.81 |
| Overall experimental uncertainty | 1.28 | |

### 2.4 Dryer Performance Evaluation Parameters

The basic standard procedure for evaluating solar dryer performance as recommended by (Leon *et al.,* 2002) was followed. The drying system was evaluated by assessing the drying rate, evaluation of percentage moisture losses, moisture diffusivity, collector and drying efficiency of the dryer.

#### 2.4.1 Percentage Moisture Loss

The quantity of moisture as a percentage of the initial mass of a material can be represented on a wet and dry basis and expressed as a percentage given by (Mohanraj *et al.,* 2009):

$$M_t = M_i - \left[\frac{w_t - w_d}{w_1}\right] \times 100\% \text{ wb} \qquad 6$$

According to equation 6, the experimental moisture content obtained from weight loss was converted to moisture ratio (Lamrani et al 2022).

$$\mathrm{MR} = \frac{\mathrm{M_t - M_e}}{\mathrm{M_i - M_e}} \qquad 7$$

However, when the equilibrium moisture content is small in comparison to the initial moisture content, La mrani et al (2022) and Ndukwu et al (2010) stated that equation 6 can be converted to equation 8 as follow.

$$\mathrm{MR} = \frac{\mathrm{M_t}}{\mathrm{M_i}} \qquad 8$$

To fit the moisture ratio curve, equations 8-10 known in the literature as Page, Henderson and Pabis and Logarithmic models (Onyenwigwe et al. 2023) were used to fit the moisture ratio data using Origin pro-2022 (Origin Inc, USA) and the best equation was selected based on the lowest chi-square ($\chi^2$) root mean square error (RMSE) and highest coefficient of determination ($R^2$) values

$$MR = \exp(-kt) \qquad 9$$

$$\mathrm{MR} = \mathrm{ae^{-kt}} \qquad 10$$

$$\mathrm{MR} = \mathrm{ae^{-kt}} + \mathrm{c} \qquad 11$$

#### 2.4.2 Drying Rate

The drying rate is determined as follows (Tonui *et al.,* 2014).

$$D_r = \frac{M_t - M_{t-1}}{dt} \qquad 12$$

### 2.4.3 Moisture diffusivity

The moisture diffusivity was determined empirically as a function of the moisture content and drying temperatures as follows (Ihediwa et al., 2022)

$$D_f = 0.000664(1 + 0.01M) \times \left[\exp\left(-\frac{3733}{T+273.2}\right)\right] \qquad 13$$

### 2.4.4 Energy analysis

The energy input from the solar collector and the energy acquired from thermal storage are both included in the energy (W) used by the drying unit to dry the leaves given as follows (Ndukwu et al., 2017)

$$Q_u = Q_c + Q_T \qquad 14$$

$$Q_c = A_c F_R [I_T \tau\alpha - U_O (T_c - T_a)] \qquad 15$$

The value of $U_o$ was taken as 10 W/m$^2$ $^o$C for a single glazed collector (Garg and Rani, 1980)

$$Q_T = m\, C_{p,s} (T_s - T_a) \qquad 16$$

The specific energy consumption is given as follows(Atalay and Cankurtaran, 2021)

$$Q_{SE} = \frac{Q_u}{w_w} \qquad 17$$

The specific moisture extraction rate is given as

$$Q_{SMR} = \frac{w_w}{Q_u} \qquad 18$$

The efficiency of a solar collector as defined by Bolaji (2005) as the fraction of heat utilized by the air exiting the collector to the incident solar energy for a particular time. The collector efficiency is deduced as follows (Atalay and Cankurtaran, 2021).

$$\eta_c = \frac{Q_u}{A_c I} \qquad 19$$

### 2.4.5 Dryer Efficiency

The thermal performance or drying rates of the products are the key factors used for the evaluation of the solar drying system efficiency (Leon *et al.,* 2002). When solar dryer works under natural convection, the efficiency of the system can be expressed as given by Forson et al., (2007)

$$\eta_{dryer} = \frac{w_w L_v}{Q_u} \qquad 20$$

## 2.5 Environmental impact assessment of the solar dryer

The environmental effect of utilizing the solar dryer was appraised using the solar dryer's $CO_2$ avoidance potential. Various approaches can be used to calculate the potential $CO_2$ mitigation. In this situation, we used coal as equivalent energy source in artificial drying and compare solar dryer energy produced to its $CO_2$ generation as follows (Simo- Tagne et al 2019)

$$M_{CO_2} = \sum_i f_i \left(\frac{f_{es} Q_d Q_u}{\eta_i}\right) EFCO_2 . FCO_2 \left(\frac{44}{12}\right) \qquad 21$$

Where $f_i$ is the fraction of dried leaves taken as 1.0, $FCO_2$ is given as the equivalent fraction of $CO_2$, taken as 0.9, $\eta_i$ is the efficiency of the collector, $Q_d$ is the mass of dried leave, $Q_u$ the is the energy utilized (MJ). $EFCO_2 = 0.0258$ kg/MJ; $f_{es} = 1$.

## 3.0 Results and Discussion

### 3.1 Influence of different collector Cover colour on the performance of the solar Dryers

The ambient condition of the drying environment is shown in Figure 2. During the course of the experiment, the ambient temperature ranged between 30.6°C in the morning to 42.3°C at noon time with an average value of 36.54°C as shown in Figure 2A. Additionally, a corresponding ambient relative humidity range of 54.7% and 24.9% was recorded for morning and noon time with an average value of 40.1 %. These values are a function of the solar radiation intensity value which ranged from 572.8 to 652.1W/m$^2$ with an average value of 621.8W/m$^2$ as shown in Figure 2B. The lower solar radiation intensity is recorded in the morning and evening, with corresponding lower ambient temperature and a higher relative humidity during these periods. Although at the early appearance of the clear sky in the morning, the solar radiation intensity might not generate enough heat to start the drying process, however, it can serve as the warm-up period for the solar dryer (Bennamoun and Belhamri 2003). On the other hand, higher solar radiation intensity recorded at noon time resulted in higher ambient temperature and lower relative humidity as shown in Figure 2. The temperature variations of the three dryers were examined as shown in Figure 3 A. Solar dryers with yellow cover recorded the highest average value of 38.68°C with a temperature range of 30.7 to 44.6°C. Similarly, solar dryers with white and blue glazing coloured cover recorded average values of 38.60°C and 38.1°C, with temperature ranges of 31.2°C to 44.5°C and 30.2°C to 43.2°C respectively. The average temperature value for the three dryers was not significant ($p < 0.05$). However, there was an average temperature variation of 0.08° C between the YCC drying unit and BCC drying unit while it was 0.58°C with a WCC drying unit. The implication is that, despite the fact that three of the covers are made of the same material and thickness, the YCC with longer wavelength in the light spectrum compared to blue has lower capacity of carrying away some of the heat released by the absorber through the cover due to its lesser energy intensity compared to BCC and WCC with shorter wave length and higher energy intensity (Bansel and Sharma 1986). Hence this might have resulted on the increased drying unit temperature compared to others.

Generally, the relative humidity decreased with an increase in the temperature as the drying progressed to noon periods. However, towards the evening, it increased with a decrease in temperature. According to Sethi et al. (2021), this is a result of the presence of water fumes remaining in the drying unit as the temperature drops, thus increasing the dampness of the drying unit. The same report has been presented by Liu et al (2007) while Lingayat et al., (2017) stated that the absence of heat from the solar radiation in off-sunshine periods allows the water vapour to hang on longer in the drying unit, hence increasing the relative humidity. However, the relative humidity shown in Figure 3B varies inversely with the temperatures of the dryers with the yellow covered dryer having the lowest average of 39.06% and a range of 53.6% to 25.9%. Similarly, the dryer with white collector cover recorded average relative humidity of 39.56% with a range of 52.4% to 27.2%, while the dryer with blue collector cover gave an average of 39.99% with a range of 53.2% and 26.3%. This result corresponds to the inverse relationship obtained by Ndukwu et al., (2022a) between temperatures and relative humidity in the drying chamber which is a function of ambient conditions. The result, however, showed that the dryer covered with yellow polythene material exhibited slightly higher average temperature within the dryer unit when compared to other dryers, especially the conventional white cover material. The implication is that since three of the covers are of the same material and thickness however, the yellow colour might have the greater potential in preventing the long wave radiation carrying some of the heat released by the absorber plates from leaving the collector through the transparent cover which is the quality characteristics advocated by Bansel and Sharma, (1986).

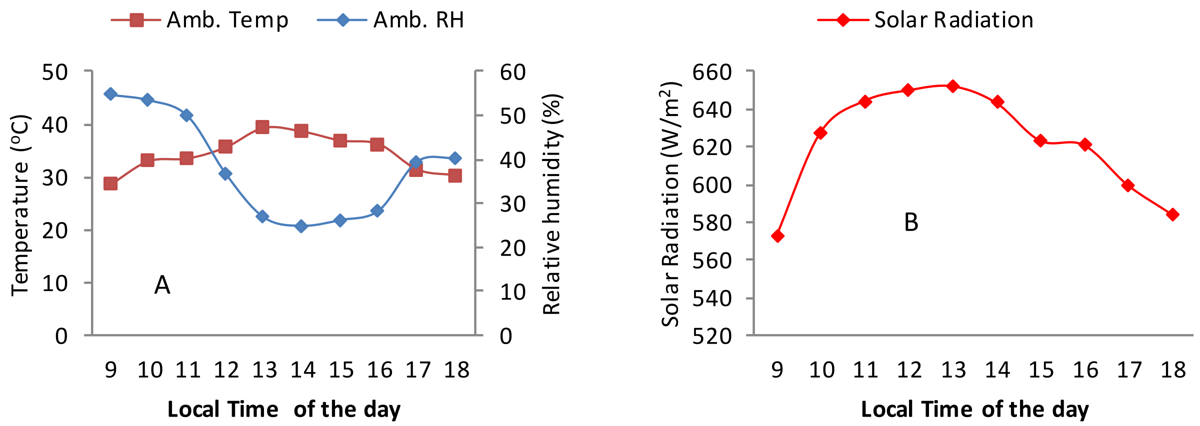


Figure 2: Ambient condition

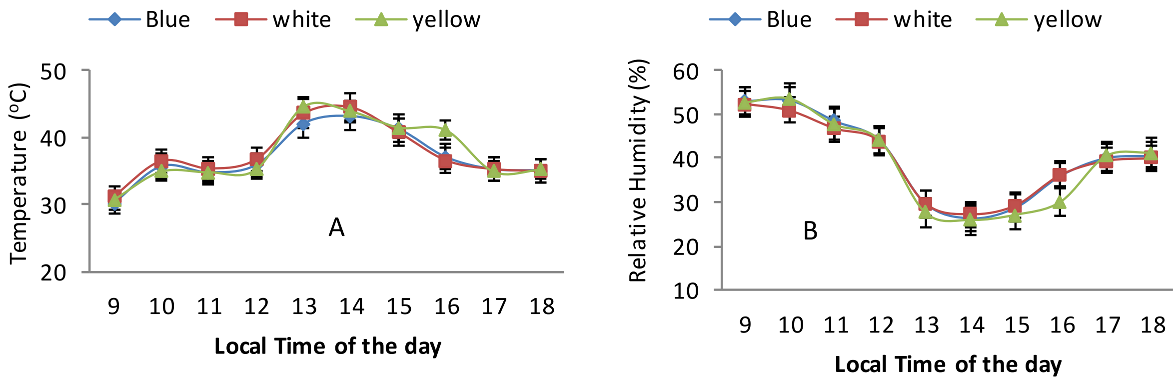


Figure 3: Drying chamber temperature and relative humidity

Figure 4 shows the picture of fresh and dried herbs in different solar dryers studied. From the graph of moisture loss in Figure 5A and 5B, the neem and bitter leaves dried in 7- 9 hours in the three dryers from the initial moisture content of 88 % w.b for bitter leave and 68% w.b for Neem to their final moisture content of 8.53±0.92 % w.b where no change in weight of the product was observed. The quick drying periods are a result of high average solar radiation intensity and low relative humidity. Comparatively the time obtained in drying the two leaves was higher than 5 h recorded for drying spearmint leaves in Algeria at a drying rate of 0.0223 kg/s but lower than 35 h for drying of thyme in the same Algerian condition (El-Sebaii and Shalaby, 2013). Benhamou et al. (2014), dried Colocynth gourd medicinal leave in 9 h using an indirect solar dryer in Algeria. The dryer averaged a temperature range of 22-57°C. At this range of temperature about 80 % of moisture was removed from the leave within this 9h. However research has shown that at lower temperature medicinal leaves can take a longer time. For example Hassanain, (2010) took about 30-48 h to dry Henna and rosemary leaves at a very low temperature of 21-25 °C using a passive solar cabinet dryer. The result obtained is also within the range of short drying time for medicinal leaves as obtained by Abubakar *et al.* (2018), Labedet al. (2016) and Nour-Eddine et al.(2015). Figure 5A showed that for drying of the bitter leaves, the moisture loss was high in WCC until 15.00 h local time when the YCC accelerated it moisture loss, however for the drying of neem, YCC dryer consistently showed a higher moisture loss from the beginning due to higher drying rate as shown in Figures 6A and 6B. However, the falling rate during the drying process is reflected in the drying rates. The moisture evaporation rate is a function of the amount of heat supplied, moisture available and the humidity of the surrounding air (Hussain and Lee, 2023). In the beginning, when there is high moisture in the leaves, the drying rate was high as shown in Figures 6A and 6B but decreases as less moisture becomes available as shown in Figures 5A and 5B for Bitter leave and Neem leave respectively. Amongst the dryers, figure 6A showed that the dryer with YCC dryer displayed the highest drying rate for Neem leave with an average value of 0.003849 kg/h followed by the dryer with WCC with an average drying rate of 0.003795 kg/h and then the blue colour covered dryer with average drying rate of 0.003762 kg/h. In Figure 6B for drying bitter leaves, the average drying rate of white colour cover was 0.004348 kg/h while blue and yellow glazing with averages of 0.00451kg/h and 0.004689 kg/h. The higher drying rate of YCC dryer is because of higher average drying unit temperature compared to others. Hence, Ayadi et al (2015) has noted that the drying temperature had the peak influence on the solar drying rate of spearmint leaves grown in Tunisia. Compared to blue colour, yellow colour has longer wavelength in the visible light spectrum which shows lower photon energy. Thus it has the possibility of lower energy dissipation losses through the cover for trapped collector heat in the drying unit which could increase the temperature build up compared to others. This might have reflected the higher drying chamber temperature observed for the YCC dryer. Thus, accelerating the drying rates of the leaves compared to others. Higher temperature being a driving force for increased drying rate on medicinal leaves has also been reported by Kouhila et al., (2002), however, Labed et al (2016) and Nour-Eddine et al. (2015) has stated that the amount of dried leaves might also be factor which is not the case in this experiment since the entire dryer received equal amount of leaves. However, these drying rates are not statistically significant ($p < 5\%$).


Figure 4: picture of fresh and dried leaves for different covers

The higher drying rate of the yellow covered drying unit is reflected in the effective moisture diffusivity presented in Figures 7 A and B. The effective moisture diffusivity was highest in the afternoon at the peak of the solar radiation but decreased in the morning and the evening. Generally, the effective moisture diffusivity for leaves is higher than most other parts of plant material due to higher porosity (Ndukwu et al., 2018).

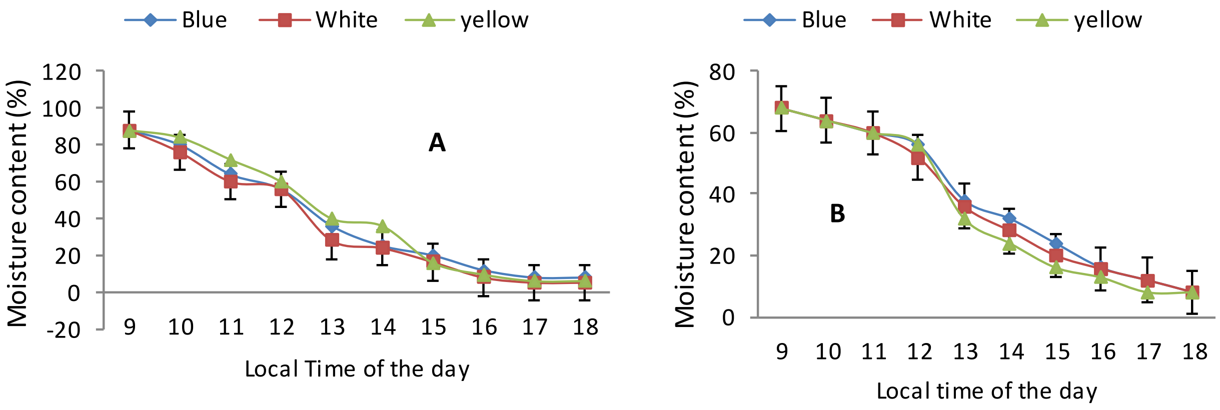


Figure 5: Moisture loss data for the leaves (A) bitter leaves (B) Neem leave

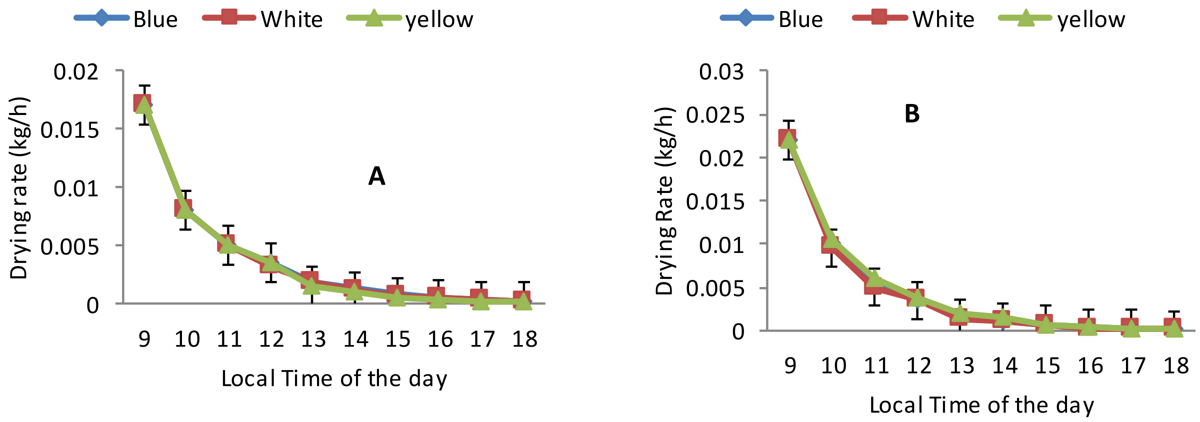


Figure 6: Drying rate (A) Neem leave (B) Bitter leaves

### 3.2 Effective moisture Diffusivity

Figure 7 shows the evolution of the moisture diffusivity for different colours of materials used as drying unit cover for drying Neem and bitter leave. Moisture diffusivity was higher in the noon period which corresponds to a higher dryer temperature and lowers relative humidity. Yellow-coloured cover presented a higher moisture diffusivity evolution for Neem leaves followed by white and blue cover in that order. This corresponds to the higher drying rate obtained for the yellow cover in Figure 6 for Neem leaver. In contrast, the white cover had the highest moisture diffusivity for bitter leave. The average effective moisture diffusivity obtained ranged from $4.003 \times 10^{-9}$ to 5.72 $m/s^2 \times 10^{-9}$ for Neem leaves and $4.04 \times 10^{-9}$ to $5.82 \times 10^{-9}$ $m/s^2$ for bitter leave. Comparatively, the effective moisture diffusivity of Neem leaves is lower than that of Bitter leaves probably due to a larger surface area as shown in Figure 4 for fresh leaves and higher initial moisture content. However, these values are higher than the effective moisture diffusivity of other solar-dried plant material beside leaves presented in Table 5 but when compared to medicinal leaves it is still within the range of moisture diffusivity obtained in the literature for leaves. For example Nourhene et al. (2008) reported effective moisture diffusivity in the range of $2.95 \times 10^{-10}$–$3.60 \times 10^{-9} m^2/s$ for solar dried olive at a temperature range of 40 to 60°C.

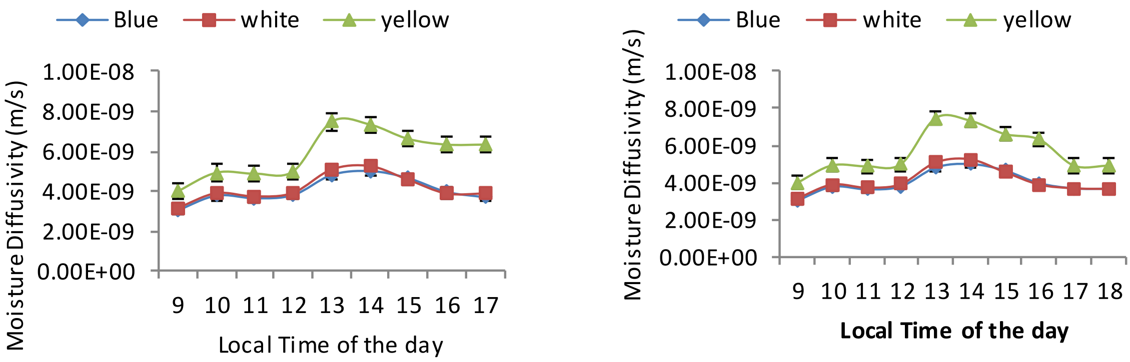


Figure 7: Evolution of the moisture Diffusivity (A) Bitter leaves (B) Neem leaves

Table 5: Comparison of effective moisture diffusivity of other solar-dried crops

| Plant materials | Effective moisture diffusivity ($m/s^2$) | Reference |
|---|---|---|
| Blanched sliced potato | $9.86 \times 10^{-11}$ to $1.54 \times 10^{-9}$ $m^2/s$ | Onyenwigwe et al (2023) |
| Blanched ginger rhizome slices | $2.6639 \times 10^{-9}$ to $2.8948 \times 10^{-9}$ $m^2/s$ | Ndukwu et al., 2023 |
| Un-blanched ginger rhizome | $2.6637 \times 10^{-9}$ $m^2/s$ | Ndukwu et al., 2023 |
| Tomato pomace | $3.2 \times 10^{-9}$ and $4.7 \times 10^{-10}$ $m^2/s$ | Badaoui et al. (2019) |
| Neem leave (yellow covered collector) | $5.72x^{9}$ $m^2/s$ | Present work |
| Neem leave (blue-covered collector) | $4.003\ x^{9}$ $m^2/s$ | Present work |
| Neem leave (white covered collector) | $4.08\ x^{9}$ $m^2/s$ | Present work |
| Bitter leave (yellow covered collector) | $5.82x^{9}$ $m^2/s$ | Present work |
| Bitter leave (blue-covered collector) | $4.04\ x^{9}$ $m^2/s$ | Present work |
| Bitter leave (white covered collector) | $4.19\ x^{9}$ $m^2/s$ | Present work |
| Tumeric | $1.852 \times 10^{-10}$ $m^2/s$ | Borah et al. (2015) |
| Mushroom | $6 \times 10^{-10}$ to $40 \times 10^{-10}$ $m^2/s$ | Reyes et al. (2013) |
| Mangoes (Amelie variety) | $4.85 \times 10\text{-}^{11}$ to $1.85 \times 10^{-10}$ $m^2/s$ | Dissa et al. (2011) |

### 3.3 Mathematical modelling

The obtained moisture content was converted to moisture ratio and fitted into three semi-theoretical models to predict the drying curve. The best-fit equation is the one with the lowest chi-square and RMSE value with the highest $R^2$ value (Ndukwu et al., 2017). The result of fitting the models with the constants and statistical data are presented in Table 6. For the three models, the $R^2$ values ranged from 0.87547 to 0.98665. These values are high, however, the Logarithmic model gave the highest $R^2$ value with the lowest chi-square and RMSE for the drying of the two leaves in different colours of collector cover. The experimental and predicted moisture ratio is plotted in Figures 8 (a) - (f) for all drying conditions with good agreement. The $R^2$ values for all drying conditions ranged from 0.9168 to 0.9952 which shows a high level of association between the plotted data.

Table 6: **Model and statistical parameters for solar drying of the two herbs**

| Model | Bitter leave | | | Neem leave | | |
|---|---|---|---|---|---|---|
| Collector cover colours | Yellow | Blue | White | Yellow | Blue | White |
| Page | | | | | | |
| k | 0.19216 | 0.21334 | 0.23865 | 0.18454 | 0.15899 | 0.17076 |
| $\chi^2$ | 0.01309 | 0.00596 | 0.00699 | 0.01627 | 0.01215 | 0.01028 |
| $R^2$ | 0.88676 | 0.94322 | 0.93759 | 0.87547 | 0.89183 | 0.90963 |
| RMSE | 0.0916 | 0.04169 | 0.04893 | 0.14644 | 0.10937 | 0.09254 |
| Logarithmic | | | | | | |
| a | 224.25057 | 2.43853 | 2.08536 | 2.29939 | 10.91689 | 2.64357 |
| k | 6.14681E-4 | 0.0676 | 0.08624 | 0.06732 | 0.01049 | 0.0521 |
| c | -223.19272 | -1.40641 | -1.06609 | -1.21739 | -9.86236 | -1.5798 |
| $\chi^2$ | 0.00285 | 0.00198 | 0.00369 | 0.00932 | 0.0037 | 0.00392 |
| RMSE | 0.01427 | 0.00988 | 0.01847 | 0.06526 | 0.02593 | 0.02743 |
| $R^2$ | 0.98236 | 0.98655 | 0.97644 | 0.9445 | 0.97436 | 0.97321 |
| Henderson and Pabis | | | | | | |
| a | 1.11497 | 1.07993 | 1.0679 | 1.13915 | 1.12456 | 1.12167 |
| k | 0.21947 | 0.23381 | 0.25682 | 0.21246 | 0.18294 | 0.19497 |
| $\chi^2$ | 0.01163 | 0.00527 | 0.00698 | 0.01401 | 0.01004 | 0.00821 |
| RMSE | 0.06979 | 0.03163 | 0.0419 | 0.11205 | 0.08029 | 0.06565 |
| $R^2$ | 0.91372 | 0.95693 | 0.94656 | 0.90472 | 0.9206 | 0.93588 |

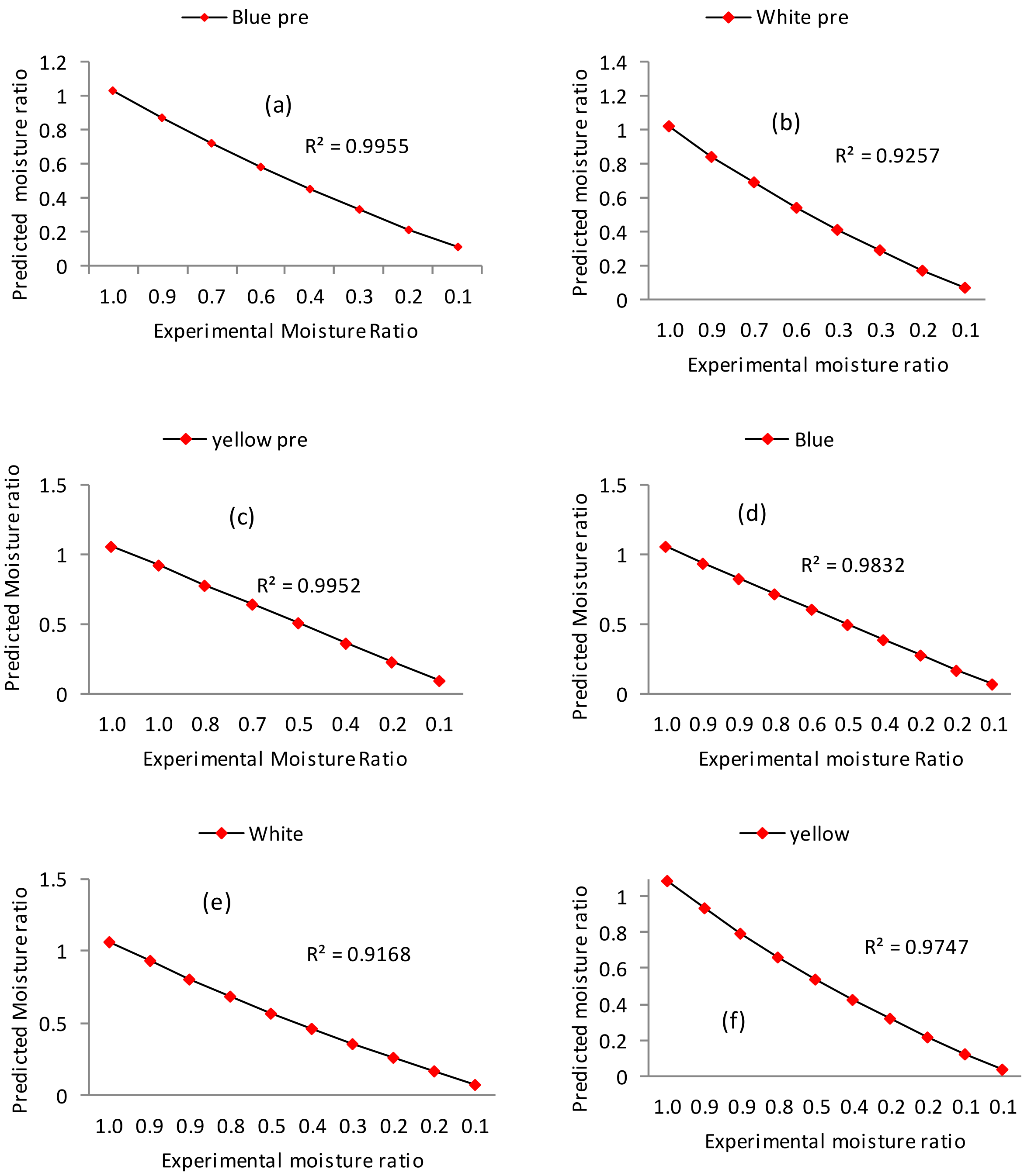


Figure 8: experimental and predicted moisture ratio (a) blue-bitter leave (b) white-bitter leave (c) yellow-bitter leave(d) blue-Neem leave (b) white-Neem leave (c) yellow-Neem leave

### 3.2 Energy and environmental impact analysis

The effectiveness of the energy utilized to dry is embodied in the overall collector and drying efficiency. The average values of the collector efficiency are presented in Table 7. The solar dryer with a yellow material-covered drying unit had the highest efficiency of 38.4 % which is higher than that of the blue and white-covered dryer by 1.43 % and 10.41% respectively. The determined collector efficiency values were higher than 24.7% and 25.56 % compared to the solar dryer presented by Isaac and Sam (2017) and Ndukwu et al (2022a) respectively in a natural convection solar dryer**.** This implies high energy utilization and also indicates the effectiveness of the design. Thus the drying efficiency exhibited by the dryers in drying Neem leaves was 10.6 % for the white and blue-covered dryer and 11.92 % for the yellow-covered dryer. Conversely, these values for drying bitter leaves were 17.62 % for white and yellow cover and 15.42 for blue cover. Higher drying efficiency of yellow coloured covered dryer is as a result of higher drying temperature of its drying unit and subsequent higher drying rate. As stated earlier in section 3.1, in comparison to blue, yellow coloured drying window cover has a longer wavelength in the visible light spectrum, which shows low photon energy, and thus has the likelihood of lower heat energy loss through the yellow coloured cover for trapped solar radiation heat in the drying unit, which could increase its temperature compared to others. This may have caused the higher drying chamber temperature with the subsequent higher drying rate observed for the dryer with yellow coloured cover. Thus because the yellow coloured covered drying window dried faster, it consumed less energy to dry he product hence the increase in drying efficiency. The drying unit covered with yellow material expanded 0.2315MJ of energy to remove 22 g and 17 g of water from the bitter leave and Neem leaves in 7 to 8 hrs while the blue and covered drying units utilized 0.2362 and 0.2321MJ of energy respectively to dry the products in 7 to 9h. Thus the in terms of energy consumption, the three dryers showed no significant difference ($p< 0.05$) . The effectiveness of the energy utilization is embodied in the specific energy consumption which is the amount of energy utilized to dry a kilogram of moisture from the product. The obtained specific energy consumption for WCC, BCC and YCC drying units were 10.55, 10.73 and 10.52 MJ/kg respectively for drying bitter leave while it was 13.65, 13.89 and 13.62 MJ/kg for drying Neem leaves respectively as presented in Table 5. This shows that the drying unit covered with yellow polyethene material was more effective in energy utilization compared to other dryers. This is due to the lower drying time exhibited by the yellow-covered drying unit. According to Madhankumer et a;l (2023), drying time is inversely proportional to specific energy consumption but directly related to specific moisture extraction rate. The values of specific energy consumption reported are lower than 48.73 MJ/kg and 90.21 MJ/kg reported on a hybrid solar dryer by Nwakuba et al (2017) due to the addition of supplementary heat. Similarly at an industrial, scale, Kaveh et al. (2021), reported specific energy consumption of 484.54MJ/kg using a semi-industrial solar dryer. Fudholi et al (2015 defined the moisture extraction rate as the turnaround result of energy utilizations and the values obtained were 0.0932 to 0.095 kg/MJ (0.333 to 0.339 kg/kWh) for bitter leave while it was 0.072 to 0.0734 kg/MJ (0.257 to 0.262 kg/kWh) for drying Neem leaves for all the three dryers. The value of SMER obtained is lower than 0.95 to 2.39 kg/kWh obtained for drying strawberries due to a lower drying period (Atalay and Cankurtaran, 2021) but higher than 0.071 t0 m0.083 kg/kWh reported by Madhankumer et al.,(2023).

Table 7: Performance parameters of different collector cover colours

| Parameters | Average values | | | Unit |
|---|---|---|---|---|
| | White | Blue | Yellow | |
| Average moisture diffusivity Neem leaves | 4.08E-09 | 4.003E-09 | 5.72E-09 | ($m^2/s$) |
| Average moisture diffusivity bitter leaves | 4.19E-09 | 4.04E-09 | 5.82E-09 | (m/s) |
| Average collector efficiency | 28.02 | 37 | 38.43 | (%) |
| Overall solar drying efficiency (Neem Leave) | 10.6 | 10.6 | 11.92 | (%) |
| Overall solar drying efficiency (Bitter Leave) | 17.62 | 15.42 | 17.62 | (%) |
| Drying time for Bitter leaves | 7 | 8 | 7 | (hrs) |
| Drying time for Neem leaves | 9 | 8 | 8 | (hrs) |
| The initial moisture content of Bitter leaves | 88 | 88 | 88 | %(wb) |

| | | | | |
|---|---|---|---|---|
| The final moisture content of Bitter leaves | 8.53±0.92 | 8.53±0.92 | 8.53±0.92 | % (wb) |
| The initial mass of Bitter leaves | 25 | 25 | 25 | g |
| Mass of water removed from bitter leaves | 22 | 22 | 22 | g |
| The initial moisture content of neem leaves | 68 | 68 | 68 | % (wb) |
| The final moisture content of neem leaves | 8 | 8 | 8 | % (wb) |
| The initial mass of Lim leaves | 25 | 25 | 25 | g |
| Mass of water removed from neem leaves | 17 | 17 | 17 | g |
| Average drying temperature | 38.1 | 38.6 | 38.68 | °C |
| Average Energy utilized | 0.2321 | 0.2362 | 0.2315 | MJ |
| Average Specific energy consumed (bitter leave) | 10.55 | 10.73 | 10.52 | MJ/kg |
| Average Specific energy consumed (Neem leave) | 13.65 | 13.89 | 13.62 | MJ/kg |
| Average Specific moisture extraction rate (bitter leave) | 0.0947 | 0.0932 | 0.095 | kg/MJ |
| Average Specific moisture extraction rate (Neem leave) | 0.0732 | 0.072 | 0.0734 | kg/MJ |

The major impact of renewable energy systems is the prevention of greenhouse gasses like $CO_2$ from entering the atmosphere, unlike other fossil-based energy sources. This capacity of solar dryers to limit environmental impact can only be visualized by calculating the $CO_2$ mitigation potential of the solar dryers. In this research as earlier stated, the energy utilized was compared to coal-powered dryers and the result of mitigated $CO_2$ is presented in Figure 9. These values ranged from 7.53 to 13.59 tons per year with the yellow-covered drying unit showing the lowest value for drying each of the products. In terms of monetary gain, the mitigated $CO_2$ can be traded as earned carbon credit. Ekka and Palanisamy (2020) gave the cost of $CO_2$ at $14.5 (₦6525) per ton, thus the mitigated $CO_2$ from this research will yield ₦49133.25 to ₦88874.75 per year in Nigeria. Thus comparatively the value of mitigated $CO_2$ is lower than 602 to 667.82 tons per year obtained by using a diesel-powered generator by Ndukwu et al (2017) for dry red chilli. However high values obtained by Ndukwu et al (2017) compared to the current dryer is due to the long drying period and the addition of supplementary energy sources.

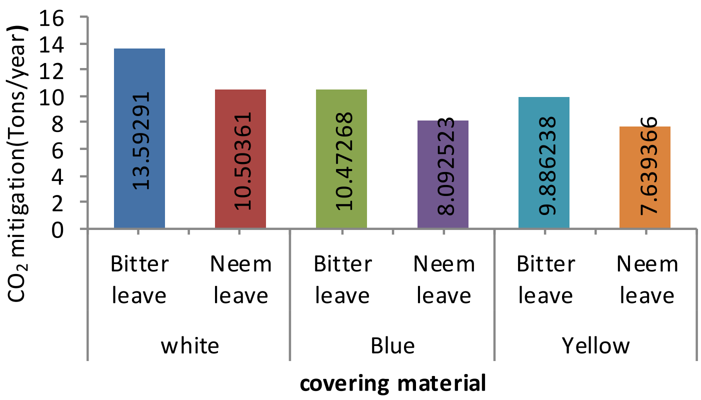


Figure 9: $CO_2$ mitigation potential of the three dryers

### 3.2 Collector material cover colour effect on the herb's natural green colouration

According to Mohana et al (2020), the colour of dried agricultural products gives the first quality impression of the product. The dried bitter leaves and Neem leaves were tested to examine the extent to which the dried herbs is close to their natural green colour after undergoing the drying process at different colour wavelength as produced by the coloured covers of the collector and drying chamber. Chlorophyll which is a group of several compounds is responsible for the green colour intensity of leaves. Drying generally has been noted to degrade the chlorophyll in green leaves but the degree of theses degradation depends on the drying methods and leaves (Rubinskienė et al., 2015). However, the present research has shown that the degree of loss can also be influenced by the light wavelength under heat. Figure 10 A-D shows colour coding for fresh, and dried bitter leaves dried in dryers with the collector covered with different coloured materials respectively. The intensity in the green red coordinates has been reported as the best attributes to compare the colour of dried medicinal leaves (Ndukwu et al., 2020). The BCC dryer with the dried bitter leaf possessed a natural green colour grading of 97 out of 255 and Neem leaves a grading of 74 out of 255 as shown in Figures 10 B and 11 B respectively. For WCC drying unit, the colour coding for dried bitter leaves was 70 out of a maximum of 255 and 66 out of 255 for Neem leaves as shown in Figures 10C and 11C respectively. Furthermore, the YCC drying unit for bitter leaves and Neem leaves was 145 out of 255 and 85 out of 255 respectively. Compared to the fresh green colour intensity the green intensity decreased by 41.21 % and 12.94 % for BCC in bitter leave and Neem drying respectively while conversely, it decreased by 57.56 % and 22.35 % for the WCC dryer. Similarly, the intensity of green colour in fresh leave decreased by 12.12% and 29.41% respectively in Bitter leave and Neem leave for the YCC solar dryer. The increase in the intensity of red colour in drying is an indication of browning (Krokida et al, 2001). In the drying of both leaves the redness intensity decreased except for the drying of the bitter leaf in the yellow-covered dryer where the redness had a small uptick. The implication is that drying the leaves in the solar dryer darkened the leaves instead of browning the leaves. This is as a result of moderate drying temperature range presented by the three dryers which ranges from 37 to 37.68 $^{o}$C. High drying temperature has been shown to brown green leaves, thus Bahloul (2009) and El Ferouali et al. (2018)stated that the best temperature to dry medicinal leaves to preserve its colour closer to the initial value is around 40 $^{o}$C. Darkening of the leaves in natural convection solar dryer has also been associated with pigment degradation (García-Moreira et al., 2023). In terms of maintaining the desired greenish colour, the result shows that on the average the yellow-covered dryer dried the leaves while keeping it close to its natural greenness followed by blue cover coloured dryer. This is in tandem with the report in literature that white coloured direct solar dryer window tanned the medicinal leaves after drying (Ndukwu et al., 2020). Several factors can contribute to the performance of yellow colour covered dryer over other colours in preserving the original colour of the leaves. Greater decrease in green intensity for products with WCC and BCC material, than YCC material, could be due to a combination of higher photon (energy) absorption by the chlorophyll and heat generated from solar radiation intensity. This is because chlorophyll, which gives leaves their green coloration, absorbs blue and white light colours when sunlight passes through the blue and white coloured covers. This blue and white light has shorter wavelengths compared to yellow light which generates higher energy intensity. This high energy it uses to breakdown water and carbon dioxide to sugar. However, since the leaves has been detached from the parent plant with no water sources at elevated temperature, this can lead to the chloroplast and plasmalemma membrane sustaining structural damage, which could negatively impact the carotenoids (Ihediwa et al., 2022). Thus, fucoxanthin which is a crucial pigment embedded within the chlorophyll pigmentation of most plants, leaches and exhibits a decrease in the green and blue coordinates. In the same way, Maillard reactions may be responsible for the decrease in green colour during drying. Additionally, Table 8 show the effect of glazing colours on drying temperatures of the leaves in the drying unit. From the ANOVA table, it is shown that drying temperature and cover colour showed a statistically significant effect on the drying of the two leaves at a 5% probability level.

**Table 8: ANOVA: Effect of collector cover colour on temperature of the drying unite**

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| DT ($^{o}$C) | 17 | 27661.8 | 94.55% | 27661.8 | 1627.16 | 97.49 | 0.000 |
| Cover colour | 3 | 744.5 | 2.54% | 744.5 | 248.16 | 14.87 | 0.000 |

| | | | | | |
|---|---|---|---|---|---|
| Error | 51 | 851.2 | 2.91% | 851.2 | 16.69 |
| Total | 71 | 29257.5 | 100.00% | | |

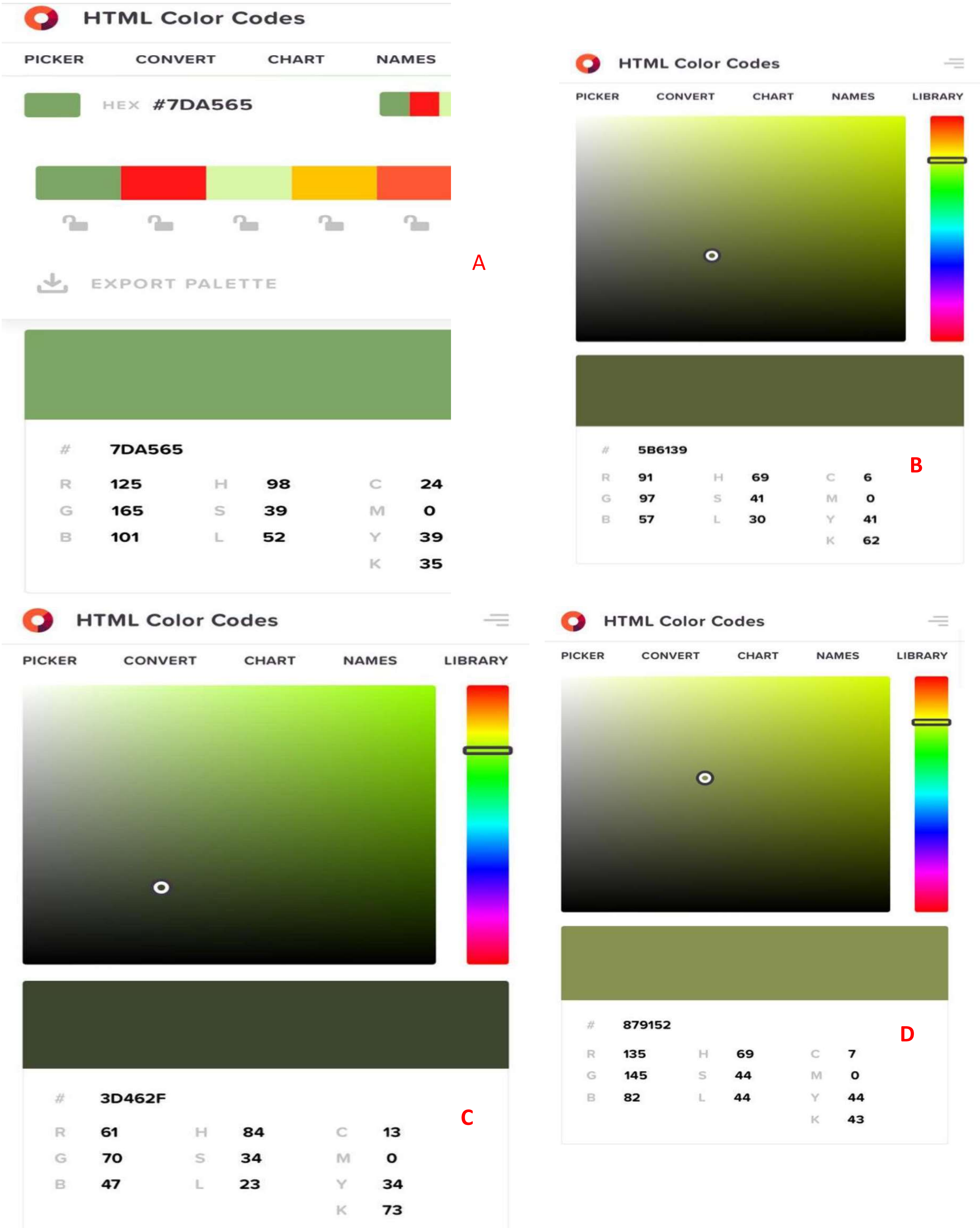


Figure 10: colour analysis of bitter leaves (A) fresh (B) blue (C) white (D) Yellow coloured glazing cover

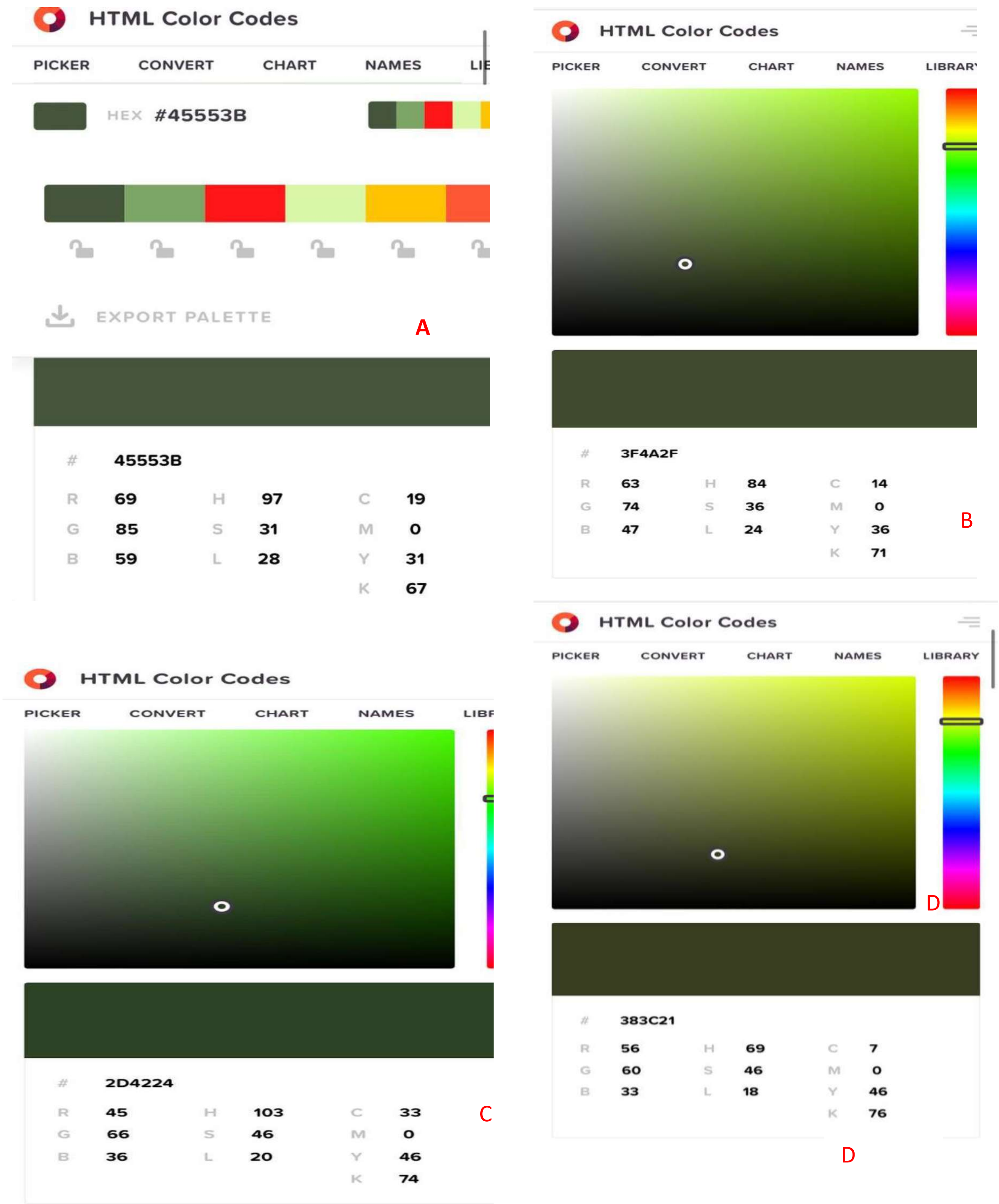


Figure 11: Colour analysis of Neem leaves (A) fresh (B) blue(C) white (D) Yellow coloured glazing cover

## 4. CONCLUSION

This study was carried out to investigate the effect of wavelength variations embodied in colour changes of the cover of a direct solar dryer on the drying characteristics and colour of dried leaves. For this reason, two coloured materials (blue and yellow) were selected to serve as the collector and drying chamber cover to vary the wavelength while the white-coloured collector cover served as the control. The results demonstrate that colour wavelength variation can affect the performance of solar dryers in drying green leaves. The yellow-covered dryer had the highest thermal efficiency of 38.8% which decreased by 1.43 % and 10.41 % for blue and white-covered dryers respectively. The average temperature variation of 0.08$^o$ C between the yellow-covered collector and blue-covered collector was obtained while it was 0.58$^o$C between the yellow and white-covered dryer. The higher internal temperature produced by the yellow-covered dryer enabled it to dry the leaves faster than other dryers with an average drying rate for Neem leaves of 0.003849 kg/h followed by the dryer with white cover with an average drying rate of 0.003795 kg/h and then the blue covered dryer with average drying rate of 0.003762 kg/h. In drying bitter leaves, the average drying rate was 0.004348 kg/h for white-covered dryers followed by blue and yellow cover with averages of 0.00451kg/h and 0.004689 kg/h respectively. The obtained specific energy consumption for the different colours of covering material for the drying units ranged from 10.52 to 10.73 MJ/kg for drying bitter leave while it was 13.62 to 13.89 MJ/kg for drying Neem leave. Comparatively, the effective moisture diffusivity of Neem leaves is lower than that of neem leaves. In terms of maintaining the desired greenish colour, the result shows that the yellow-covered dryer dried the bitter leaf while keeping it close to its natural greenness. A similar best condition is observed with the drying of Neem leaves with blue-covered material in comparison with collectors covered with white and yellow-coloured materials. Non-browning of leaves was observed, instead, they darkened which was indicated by the decrease in the red colour intensity for the leaves. The fitting of the moisture ratio showed that the logarithmic model is the best in predicting the drying curve under all the colour cover drying conditions. The obtained result will assist the solar dryer fabricators to select the appropriate glazing cover design to improve solar dryer performance. Future research will extend the research to other colours and compare the performance. Heat transfer analysis will be carried out for optimization purposes.

**Declaration of Competing Interest**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability** Data will be made available on request.

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