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DIFFUSE SOLAR SYSTEM DESIGN AND UTILIZATION IN AGRICULTURE AND DOMESTIC APPLICATIONS

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Abstract

Diffuse solar radiation is a component of total solar radiation that is good for low temperature grade heating. Since the portion of the scattered radiation from the sun, which consists of short and long waves, that reaches the earth is diffused, its utilization in Agriculture as this paper suggested, has multiple phase change material, which as well could serve as heat exchange for domestic (residential) applications. The Diffuse Solar System designed, consists of three functional units: the solar collector, thermal storage (heat sink) and a dryer cabinet. The thermal storage ranges from 140 – 150^{0}F (60 – 50^{0}C) for heating system and 60 – 70^{0}F (15 – 20^{0}C) for residential cooling. Likewise, a natural convection solar dryer with collector efficiency of about 42% and drying efficiency of about 53% would dry tomatoes with initial moisture contents of 94% wet basis, to safe moisture content of about 4% wet basis and 35.2 – 86.8% ascorbic acid (vitamin C) retention with acceptable colour and texture.

Keywords: ***Solar radiation, Heat sink, Ascorbic acid, Collectors, Reflectors, Yeast/mould count and Efficiency.***
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Introduction

The only completely pollution free energy source is sunlight and its conversion into other energy forms, could be researched, to contribute significantly to satisfying the energy demands of the Nation. It follows then that a decrease in use of the other polluting forms of energy will lead to decrease in water pollution, oil spills, problem of radioactive waste disposal and air pollution which includes particulates, sulphur oxide, carbon monoxide and hydrocarbons. Since the industrial revolution, fossil fuels – coal, oil, and natural gas has been the most important source of energy without considering its reserves. These led to unending form of atmospheric pollution which depletes the earth’s ozone layer produced by acid rain such as sulphuric and nitric acids, directly endangering the life of fish, animals and vegetation. Besides, liberating poisonous meals, these metals may find their way into rivers and lakes and thus become health hazards, therefore the need to trap energy from the sun becomes inevitable **(Ezekwe and Ezielo 2009)**.

Eke (2010), agreed with **Simonson (2009)**, that the energy flow sheet of the earth by Hubbert Scientific American in Figure 1, generates continuous flux of energy. This heat is lost into space in the form of long wavelength (infrared) electromagnetic radiation. The rate at which solar radiation reached the upper limits of the earth’s atmosphere on a surface normal to the incident radiation and at earth’s mean distance from the sun is called solar constant. The electromagnetic radiation has a wavelength range of 0.28 – 30μm. With the exception of the bare plate and focusing collectors, the cylindrical, the covered plate and the suspended plate collector have a transparent cover which allows solar radiation but opaque to long wave radiation from the absorber plate. This can be made of polyethylene, polyvinyl or glass. Each has its own advantages and disadvantages, while research showed that the optical properties of transparent cover materials usually glass or thin plastic film, that are of most importance in solar collectors are the refractive index which determines the reflection losses from the cover and the "extinction" coefficient which determines the absorption losses in the cover **(Ezeike, 2008)**.

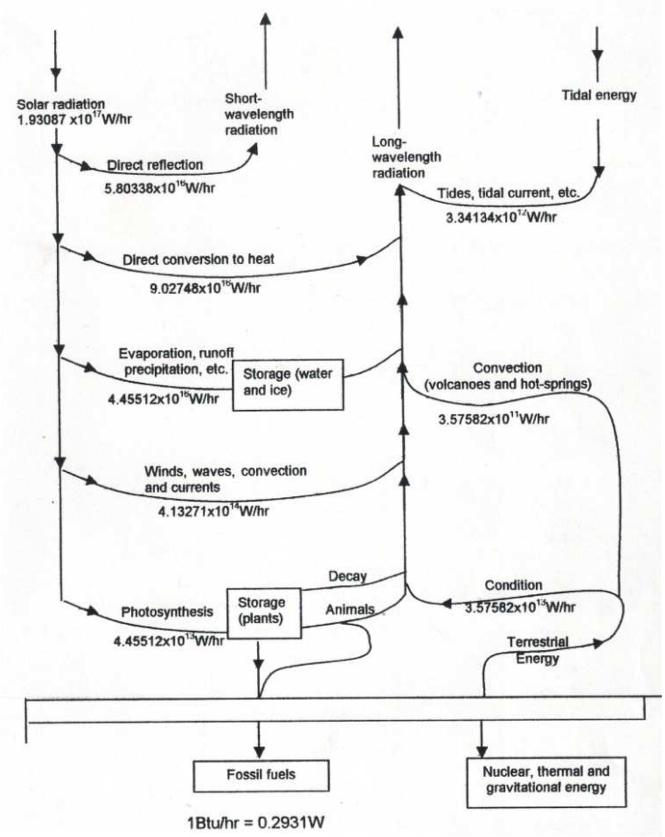

Figure 1: Energy Flow Sheet for the Earth
Source: (Eckhoff 2010; Linsley et al. 2006).

Diffuse Solar System Design and Applications:

Design consideration

The major design consideration is in concentrating the radiation by means of reflection with three functional units namely: a flat plate collector, solar thermal and circulation through pipes, storage of solid rock and wax media, and dryer cabinet. In most proposed and currently used collection systems, the Diffuse Solar Technology System which converts sunlight into heat for room temperature regulation and drying agricultural products is a better option for system deign. The collection are typically made up of a black, sunlight absorbing metal surface covered with several layers of glass to minimize radiative heat loss. The effectiveness of this system is enhanced by the greenhouse effect. The glass is transparent to the sunlight of shorter wavelengths, but absorbed and traps the longer wavelengths radiated back by the hot surface. The fluid circulated through pipes in contact with the surface is heated and used to convey the heat to its point of use. The diffuse solar system was designed to be used in water and comfort heating or cooling of residences and for on-farm drying of vegetables, tomatoes and sliced yams. The deign considered the drying rates, moisture contents, ascorbic acid content, colour texture, bacterial, yeast and mould load.

Construction materials selection is based on such properties like reflectivity, conductivity, thermal action etc. Other considerations are socio-economic. They include ease of construction using readily available local materials, efficiency, cheapness, durability, ease of operation and maintenance, simplicity of design and adaptation into household and agricultural uses. The equipment consists of three main components – **a solar collector unit, a solar storage unit and a heat sink (with dryer chamber).** These units were linked together by means of pipes, pumps and valves.

Solar collector

This was of the suspended plate type dimensions, 283 x 130 x 150cm (length, width and depth respectively), externally. The material of the box shall be soft wood of thickness 2cm. absorber plate shall be of galvanized steel metal sheet of thickness 0.05cm. The absorber was covered with a thin layer of black emulsion paint to act as a black body. Likewise, the inside of the box should be painted black to enhance absorption of heat. The absorber plate should be suspended 4cm from bottom insulation. Plane glass shall be used as the transparent material. 8cm diameter pipes were to be used for the inlet and outlet of hot air from the collector. The collector should be suspended on stands 90cm above ground level meant to track the sun, which was innovated from the former work of **Igbinoba (2010)**, who used a thickness of 5cm absorber plate without galvanized metal sheet.

Storage (distribution) system:

The intermittent nature of solar energy makes storage system a necessity. Thermal energy is usually stored in a heat reservoir (heat sink). The sink may be as simple as an insulated tank of liquid or salts. During heating, heat is absorbed into the sink from fluid by use of pump (1), heated in the collector, during favourable solar energy-collecting hours. When the stored heat is needed, another fluid heated at the heat sink is circulated through the pump (2). This fluid then conveys the heat to the desired areas of use. The heat is stored in the heat sink by raising the temperature of the storage medium by means of phase change material such as salt mixture of organic solid that melts, example candle wax, which absorbs heat when heated by the hot fluid from the collector. Likewise, agricultural products like vegetables and tomatoes could be dried at the heat reservoir (heat sink).

For cooling purposes, when the heat at the sink is used up or extracted, the phase change material cools to a temperature lower than the ceiling (room) temperature. Hence, cold fluid circulates by the use of pump (2), to the ceiling. Here, it absorbs heat and flows back to the sink where there is heat exchange through the phase change material. This invariably cools the room at any desired temperature. At this instance, pump (1) is closed to avoid flow back system. Figure 4 is a typical storage distribution of diffuse solar system involving a heat sink. The system can also be used for cooling in the summer, by removing heat from the interior during the day and storing it in the sink, until it can be released for use when necessary.

Electrical design

These consisted of the electrical instrument and electrical sensing instrument incorporated into the system. The electric pump which drove the suction fan was of 3-phase system. Thermocouples used were made by soldering copper wire and copper-constantan wire to form the hot and cold (reference) junctions. The cold junctions were maintained at ice temperatures for room cooling operation, while the hot junctions were in the heat sink (collector) for heating and drying operations. A potentiometer is used to sense the temperature variations.

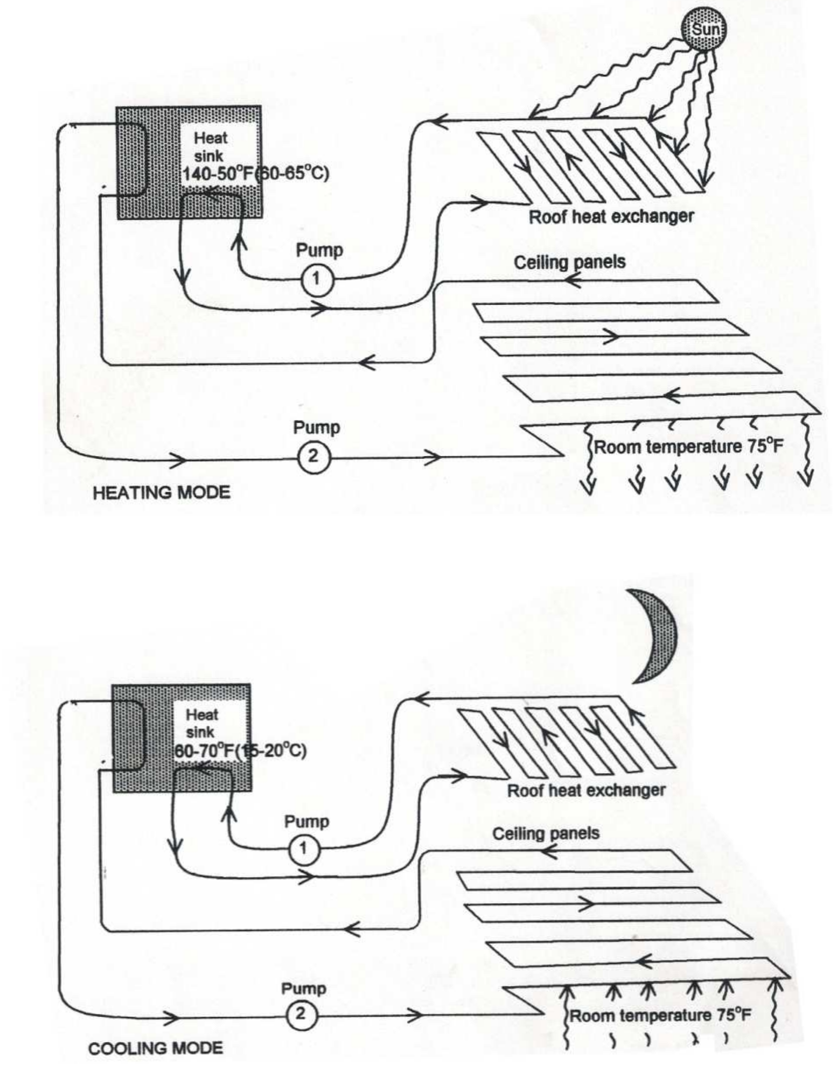

Figure 2: Storage of Thermal Energy from the Sun

Analysis:

Heat inflow into the collector:

Figure 3 shows the cross-section of inlet pipe end of the collector. The heat inflow into the collector was shared in such a way that ¼ flows under the absorber while ¾ flows on top. The absorber plate and the inlet should be located in such a position as to allow such volume inflows irrespective of velocity. Therefore, for the same volume (V) = θ (x-section) and area of triangle (A) is:

$$A = 2\left[\frac{1}{2} r sin\frac{\theta}{2}.cos\frac{\theta}{2}\right] \qquad (1)$$

$$= r^2 sin\frac{\theta}{2}.cos\frac{\theta}{2} = r^2 sin\theta$$

Area of triangle + shaded portion is

$$\frac{D^2}{4} X \frac{\theta}{2\pi} \ ,$$

area of the shaded portion is

$$\frac{\pi D^2}{4}.\frac{\theta}{2\pi} - \frac{r^2}{2} sin\theta \ = \ \frac{\pi D^2}{4x4}$$

$$\therefore \ \frac{r^2}{2}\theta - \frac{r^2}{2} sin\theta \ = \ \frac{r^2}{4}$$

$$r^2\theta - \mathrm{r}^2\theta\frac{\pi r^2}{2}$$

$$\theta - sin\theta = \frac{\pi}{2} = 1.57$$

Energy output from the collector:

Ambient inlet temperature (T_{in}) measured and collector exhaust temperature (T_{out})

Measured temperature rise Δ T = $(T_{out} - T_{in})^0$C (1)

Velocity of air V = 668m/min = 113.33cm/s

Diameter of the pipe, D = 8cm

Cross sectional area of pipe $A = \frac{\pi D^2}{4} = 50.26cm^2$

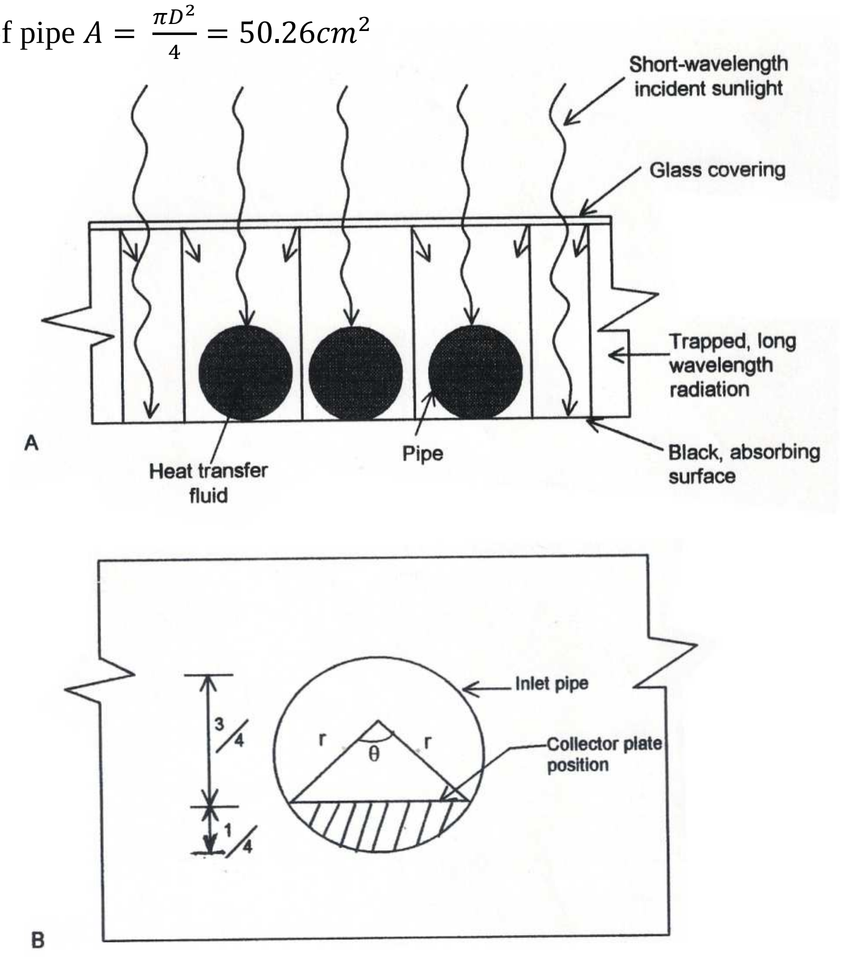

Figure 3: Collector System for Converting Sunlight into Heat

Average energy collected is 50260W (50.26kW) and average daily efficiency with the use of insulation data recorded by pyranometer (9PSP – 14875F3) and glass WG295 (general glass) shoot glass is 71.99%, considering unnecessary influences like power failure, cloudy weather etc.

Then volume ratio of hot air:

$$V = Va \tag{2}$$

$$= 1113.33\ X\ 50.26 = 55955.96cm^3/s$$

$$density\ of\ air\ used\ \rho\ = 0.0013g/cm^3$$

$$mass\ flow\ rate\ m = \ \rho\ V \tag{3}$$

$$= 55955.96\ X\ 0.0013 = 72.74g/s$$

$$The\ rate\ of\ energy\ collection\ Q = M(C_p)a\Delta\ T \tag{4}$$

where:

$(C_p)a$ = Specific heat air $(0.24 cal/g^oC)$

The energy collection rate per unit area of absorber:

$$hc = \frac{Q}{Area} = \frac{m(C_p)a\Delta T}{A}$$

where: $A \ = \ Area\ of\ absorber = 3.679m^2$

$$hc = Heat\ collection\ rate\ per\ unit\ area\ of\ abosrber$$

$$for\ \Delta T = \ 12^0C$$

$$Q = m\ (C_p)a\Delta T = 72.74\ X\ 0.24\ X\ 12$$

$$= 209.49 cal/sec\ X\ (4.2J)$$

$$= 879.896 J/s$$

$$Q = 879.896W$$

$$\therefore hc = \frac{Q}{Area} i.e. \frac{5.7}{Area} = \frac{879.896}{3.679} = 239.15 W/m^2$$

Solar Dryer Performance Efficiency, Collector Efficiency and Drying Evaluation:
Komolafe and Osunde (2005), sampled their works based on **ASHRAE (2004),** an interval of 2hours for moisture content under drying at varied stages, using vacuum oven drying at 70^0C for 6hours. The following data were taken every 2hours: solar irradiation intensity (I), wind speed (W_{sp}), wet bulb temperature (T_w), dry-bulb temperature (T_n), relative humidity (RH), collector outlet temperatures (T_c) and dry chamber air outlet temperature (T_p). The ascorbic acid (vitamin C) content from the diffuse system shall be found using titratory method by treating the sample with mercuric chloride into soluble micurous chloride separated and titrated with standard iodine solution. The unreached iodine should be estimated with standard theosulphate. The colour and the texture quality shall be evaluated using point eight scoring multiple comparisons test method (**Ihekoronye and Ngoddy, 2010),** while the wholesomeness of the dried tomatoes shall be enumerated using plate count method (**Rufai, 2008; Taylor 2008; Willer 2009).**

Komolafe and Osunde (2005)'s solar dryer performance efficiency and collector efficiency determination arrived at the following results through Eqs (5 – 7), viz:

$$\varepsilon_{co} = Ma\ C_{pa} \frac{(T_o - T_1)}{Ace\ I}, \qquad (5)$$

$where$:

$$\varepsilon_{co} = Colector\ (dryer)$$

$$Ma = Air\ mass\ flow\ rate, kg/s$$

$$C_{pa} = Specific\ heat\ capacity\ of\ air, J/kg^0C$$

$$Ace = Effective\ collector\ area, m^2$$

$$T_o = Average\ dryer\ temperature\ (Collector\ air\ out\ temperature^0C$$

$$T_1 = Collector\ air\ inlet\ temperature,\quad {}^0C$$

$$I = Average\ dasily\ insolating\ W/\ m^2$$

$$But\ Ma = \frac{AVE\ T_0 \rho}{T_1} \qquad (6)$$

$Where$:

$A = Collector\ air\ inlet\ area\ m^2$

$V = Wind\ velocity\ m/s$

$E = Effectiveness\ of\ openings\ (0.5\ to\ 0.6\ perpendicular\ winds\ and\ 0.25\ to\ 0.35$
$for\ diagonal\ winds$

$T_0 = Average\ dryer\ temperature\ (collector\ outlet\ temperature\ {}^0C$

$\rho\ = Density\ of\ air, kg/\ m^3$

$A = 0.37m^2, V = 1.65m/s, E = 0.426,\ T_0 = 0.44^0C,\ T_1 = 31^0C, \rho\ \ at\ 31^0C = 1.293kg/m^3$

$$Ma = \frac{0.37\ X\ 1.65\ X\ 0.426\ X\ 1.239}{31} = 0.476kg/s$$

$$C_{pa} = \frac{1004.5}{kg^0C}, Ace = 0.37m^2, I = 391W/m^2$$

$$\therefore\ collector\ efficiency\ is:$$

$$\varepsilon_{cd} = \frac{0.476\ X\ 1004.5\ X\ (44 - 31) X\ 100}{0.37\ X\ 391}$$

$$= \frac{6212.75}{144.67} = 42.9\%$$

For drying efficiency(ε_{cd}):

$$(\varepsilon_{cd}) = \frac{WtLv}{IAcet}, \qquad (7)$$

where: $(\varepsilon_{cd}) = System\ drying\ \%, t = drying\ time, sec, Lv = Latent\ heat\ of$ $vaporizationJ/kg, I = average\ daily\ insulation\ incident\ on\ collector, W/m^2\ , Wt =$ $wt\ of\ evaporated\ water\ kg, = effective\ collector\ area\ m^2.$

I, incident on the collector, was found from the data collected during the crop drying to be$391W/m^2$ *. Latent heat of vaporization is given by* ***Ashrae*** **(2004)**, *as* $2401000J/kg$ *at temperature* 42^0C *and* 31^0C *respectively. Based on the given data, these calculations hold*:

$$(\varepsilon_{cd}) = \frac{WtLv}{IAcet} \tag{8}$$

$$But\ Wt = \frac{(Mci - Mcf)}{I}\ Dm \tag{9}$$

$$Dm = \frac{Wm - Wm\ X\ Mcw}{100} \tag{10}$$

$$Then\ Dm = \frac{2.5 - 2.5}{100}\ X\ 94 = 0.15kg$$

$$\therefore Wt\ = \frac{(15.67 - 0.042)}{1}\ X\ 0.15$$

$$= 0.15kg\ (0.00234m^3\ Volumetric\ or 2.34\ lit)$$

$$Ace\ for\ dryer = 0.37m^2, Lv = 2401000J/kg, I\ = 391W/m^2, t\ = 2.5days\ of\ 8hrs\ effective\ drying\ time.$$

$$\therefore t = 2.5\ X\ 8\ X\ 3600 = 72000secs$$

$$\therefore \varepsilon_{cd} = \frac{2.34\ X\ 240100}{391\ X\ 0.37\ X\ 72000}\ X\ 100 = 53.9\%$$

The ascorbic acid content, analysis for variance colour, texture evaluation, total aerobic count, yeast and mould count were tabulated as follows:

Table 1: Ascorbic Acid Content of Tomatoes per 100kg

	1^{ST} BATCH				2^{ND} BATCH			
T_c (mm)	ASCSOD (mg)	R (%)	ASCSUD (mg)	R (%)	ASCSOD (mg)	R (%)	ASCSUD (mg)	R (%)
5	20.30	86.0	6.16	26	20.70	87.7	7.04	29.6
10	20.20	85.5	5.28	22.4	19.80	83.9	7.04	29.6
15	19.30	81.7	4.40	18.6	19.80	83.9	6.16	26.0
20	7.90	33.5	3.60	14.8	8.80	37	4.40	18.6
Fresh tomatoes		23.6mg						

where:
T_c = Thickness of tomatoes
ASCSOD = Ascorbic contents of solar dried tomatoes
ASCSUD = Ascorbic contents of sun dried tomatoes
R = % ascorbic acid retention

From the Table 1 above, (R) decreases as (T_c) increases but (ASCSOD) has encouraging result than (ASCSUD) for ascorbic acid content need for the body.

Table 2: Analysis of variance for colour evaluation of solar dried tomatoes

Source of Variation	df	Ss	Ms	F
Samples	3	40.22	13.4	0.01
Judges	8	2	0.25	
Error	24	437.78	18.24	
Total	25			

Where:

df = degree of freedom, S_s = variation standard for solar dried, M_s = variation standard for fresh

Comparing the F – calculated = 0.01 with table value = 3.01 at 5% level and 4.72 at 1% level, since the calculated F value = 0.01 < 3.01, the F value in Table 2 indicates **no significant difference in colour between S_s and M_s.**

Table 3: Analysis of variance for texture evaluation of solar dried tomatoes

Source of Variation	df	Ss	Ms	F
Samples	3	12.66	4.22	0.52
Judges	8	2		
Error	24	-192.66	0.25	
Total	25	-178	8.02	

Since F – calculated = 0.52 < 3.01, it indicates that there is no significant difference in texture of the dried tomatoes to that of the fresh one.

Table 4: Total aerobic plate count in colony forming units per gramme dried tomatoes

	1ST BATCH		**2ND BATCH**	
T_c (mm)	PCSOD (cfu/g)	PCSUD(cfu/g)	PCSOD(cfu/g)	PCSUD(cfu/g)
5	40 x 10^2	320 x 10^3	<30	210 x 10^3
10	100 x 10^2	260 x 10^4	90 x 10^2	240 x 10^4
15	120 x 10^2	300 x 10^4	110 x 10^2	280 x 10^4
20	160 x 10^2	TNTC	140 x 10^4	TNTC

where:
PCSOD = Plate count for solar dried tomatoes
PCSUD = Plate count for sun dried tomatoes
TNTC = Too Numerous to Count
COP = Cut off point = 1 x 10^5

From Table 4, the (cfu/g) for PCSOD is lower than PCSUD, thus, showed better performance in usage.

Table 5: Yeast and mould count for dried tomatoes in colony forming unit/gramme

	1ST BATCH		**2ND BATCH**	
T_c (mm)	PCSOD (cfu/g)	PCSUD(cfu/g)	PCSOD(cfu/g)	PCSUD(cfu/g)
5	< 1 x 10^1	< 1 x 10^1	< 1 x 10^1	
10	< 1 x 10^1	< 6 x 10^1	< 1 x 10^1	
15	< 1 x 10^1	< 1 x 10^3	2 x 10^1	
20	3 x 10^1	15 x 10^3	12 x 10^1	

Table 5, as well showed better performance in dry condition of (cfu/g) while dried in PCSOD than in PCSUD.

Conclusion

1. The Diffuse Technology System with flat – plate collector made to track the sun is very effective in obtaining the low-grade heat much needed in drying temperature as high as 150^{0}F (65^{0}C) should be recorded on the heat sink, while temperature loss should be avoided.
2. The storage system is an effective means to keep up drying during the night or during periods of bad weather when no sun is readily available.
3. The rate of drying or heating is increasing and the drying time also reduced by the use of diffuse solar system when compared with the controlled dried under existing weather condition. There is colour maintenance, which should be different from controlled environment. Therefore, the design should be ideal for domestic usage, industrial usage and agricultural products
4. The pipes carrying the solar heat should be insulated so as to prevent heat loss.

5. To improve the heat input in the storage medium, a second collector can be mounted to heat up the storage at known air velocity and temperature or the heated air drying cabinet should be directed into the storage medium instead of escaping into the atmosphere.
6. From the design, the performance evaluation of solar vegetable dryer and the efficiency of the solar dryer was found to be 42.9% which falls with the acceptable range for natural convention solar dryer (range being between 15 – 30%). While the drying system efficiency shows 53.9%, which is high (about 11% increase). It has about 66% improvement in the rate of drying over sun drying for tomatoes and other perishable agricultural products.
7. Therefore, a natural convention solar dryer with collector efficiency of about 42.9% and drying efficiency of about 53.9% could dry tomatoes initial moisture content of 94% wet basis to a safe moisture content of about 4% wet basis to give dried production with about 35.2 – 86.8% ascorbic acid (vitamin C) retention, well acceptable colour and texture.
8. For maximum dryer capacity utilization, slice of 15mm thickness is recommended to avoid having poor quality and production.
9. The design of diffuse solar energy utilization for domestic and agricultural application shall be based on the recommended design, or design within acceptable natural convention solar dryer range between 15 – 30%.

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