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Amla (*Emblica officinalis*) Drying in Solar-assisted Heat Pump Dryer

P.L. Singh[*1] and S. Singh[*]

Abstract – *An attempt has been made to study dehydration of Amla (Indian goose berry) fruits. Amla (Emblica officinalis) fruits contains high amount of vitamin-C, which is volatile and highly susceptible to heat. Heat pump drying provides a controllable drying environment (temperature and humidity) for better products quality at low energy consumption. Amla was dried in the dryer at relatively lower temperatures (35-50°C). The vitamin-C content in the heat pump dried Amla was improved up to 88% as compared to the open sun drying. There was significant reduction (five-fold) in microbial counts in the Amla dried in the heat pump dryer. The drying time in the dryer was reduced with increase in drying temperature. Drying behaviour was best fitted with the Henderson and Pabis drying model. The total COP (heating and cooling) of the heat pump was 4.8. The average COP along with the solar heating system was improved to 6.6. Thermal efficiency of the dryer was 24-28% for Amla fruit drying.*

Keywords – Amla *(Emblica officinalis),* coefficient of performance, dryer efficiency, solar-assisted heat pump dryer, vitamin-C.

1. INTRODUCTION

Amla *(Emblica officinalis)* or Indian gooseberry is known for its medicinal and therapeutic properties from ancient time in India and considered a wonder fruit for health conscious population. Amla tree is native to tropical Southeast Asia particularly central or southern India, Pakistan, Bangladesh, Sri Lanka and Southern China. It is rich in vitamin 'C' and has played an important therapeutic role from time immemorial and is frequently recommended for its synergistic effects in both Ayurvedic and Unani systems of medicine. The general chemical composition of the Amla fruit [1] is given in Table 1. Amla fruits tissue contain protein concentration three fold and ascorbic acid concentration 160-fold over those of apple. The fruit also contain considerable higher concentration of most mineral and amino acids than apple. The major problem faced by industries is that the raw fruits are available only for short period (October to January). The fruit may be preserved by drying in the season and can be used for rest of the year. Sethi [2] recommended blanching of Amla for four minutes in boiling water before drying.

Blanching prevents non-enzymatic browning and retains better colour of the processed product during storage, because of higher degree of inactivation of polyphenol oxidase. Because of its heat sensitivity, the Amla is very difficult to dry while maintaining its nutritional quality. No significant information on drying processing of Amla is available in the literature.

Drying of the Amla in open sun is the most widespread preservation technique. Since sun-drying process is relatively slow depend upon weather, considerable losses can occur. In addition, a reduction in product quality takes place due to loss of vitamins, change in physical appearance, colour, insect infestation, enzymatic reactions, growth of microorganism and development of mycotoxin [3].

To increase moisture carrying capacity of the drying air, the commonly available solar and mechanical dryer (for agricultural crops) maintains relatively higher temperature (60-90°C) for drying the product [4], particularly in humid environment. Whereas, in the case of dehumidifier based heat pump dryer, drying can be performed at relatively lower temperature due to control over humidity. The heat sensitive products such as Amla and other medicinal crops are likely to lose important vitamins and essential oils while drying in mechanical or solar dryer. Murthi and Joshi [5] tried fluidized bed drying of the Amla flakes. They found the reduction in the drying time in the fluidized bed dryer as compared to tray drying above 60°C. However, there was severe reduction in vitamin-C content in Amla after 60°C. In the case of dehumidifier based heat pump dryer, drying can be performed at relatively lower temperature due to control over humidity. For medicinal and aromatic crops, the heat pump drying technology can preserve its natural ingredients and functionality [6]. In the heat pump dryer, energy cost can be potentially reduced of the conventional dryers [7]. Many type of the heat pump dryer have been developed in two decades. However, among the heat pump assisted drying technology, the one is gaining attention and popularity is the solar assisted heat pump drying system. While enough is known about heat pump dryers and solar systems, optimal design and integration of a solar assisted heat pump dryer remains a challenging task [8], [9].

Several numerical and experimental investigations were carried out by many researchers on the heat pump dryer for drying different biomaterial products [10]-[14].

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However, only limited literature is available on solar assisted heat pump dryer. In this paper, blanched and deseeded Amla fruit drying behaviour in the heat pump dryer (20 kg/batch capacity) has been studied and analysed. The ascorbic acid (vitamin-C) content and microbial counts in the dried Amla fruit (at different drying temperature) was measured and compared with the open sun drying. Increase in COP of the heat pump with solar air heating system and solar energy supplementation to heat pump dryer at different drying temperature was measured and analysed.

Table 1. Chemical composition of Amla (Emblica officinalis) fruit.

Constituent	Amount (%)	Constituent	Amount (mg/100g pulp)
Fibre	1.9-3.4	Vitamin-C	200-1800
Carbohydrates	14.1-21.2	Lysine	17.0
Protein	0.50	Tryoptophan	3.0
Fat	0.10	Methionine	2.0
Minerals	0.5-0.7	Iron	1.20
Calcium	0.012-0.026	Nicotinic acid	0.20
Moisture	77.1-84.2	Riboflavin	0.03

2. METHODOLOGY

2.1 *Solar Assisted Heat Pump Dryer Details*

The solar assisted heat pump dryer of 20 kg/batch (Figures 1 and 2) was consisted of the heat pump (dehumidifier), drying chamber, circulation fan, drying trays, solar air heater, electrical backup and blower. Specification of the solar assisted heat pump dryer is given in the Table 2. The heat pump system consisted of condenser, evaporator, hermetic compressor, thermostatic expansion valve that were connected by using copper tubes. The refrigerant R22 was used as the working fluid. An axial fan was provided between condenser and evaporator to circulate air through evaporator and condenser. The heat pump was connected to the drying chamber. The drying air temperature in the chamber was controlled with a microprocessor based temperature controller. Electrical heating back up (1.0 kW) was also provided to supplement heat during cloudy and inclement weather and off sun shine hours. The solar air heater (2 m^2 collector area) provided to supplement heat to the dryer. A centrifugal blower has been provided to re-circulate the dehumidified and hot air.

2.2 *Amla (Emblica Officinalis) Drying and Drying Behaviour*

The fresh Amla was procured from the local market. It was blanched in the boiling water for 4 minutes [2]. The blanched Amla was deseeded and cut into six pieces. The Amla pieces were uniformly spread at the rate of 3 kg/m^2 on the drying trays. Quantity of Amla loaded in the dryer, moisture content, drying time, air temperature inside the chamber, relative humidity, air recirculation rate, ambient temperature, solar insolation measured during drying tests at the regular intervals.

The critical moisture content of the Amla during drying was measured at different interval by oven drying method [15]. To measure the moisture content, the leaf dried in hot air oven initially at 105±1°C for 2 h and subsequently at 80±1°C unless the weight became constant. The moisture content was calculated on wet basis as well as dry basis too. The data of the equilibrium moisture content for Amla reported by Methakhup *et al.* [16] was used as reference. Drying data were fitted to the thin layer drying models namely, Wang and Singh model [17] and Henderson and Pabis model [18].

The correlation coefficient squared (r^2) and standard error (s) was used as criteria for accuracy of fit [19]. The average of the relative percentage difference between the experimental and predicted values of the mean relatives deviation modulus (P) defined by Equation 3 were also used to define model accuracy [19].

Wang and Singh drying model

$$MR = 1 + b*t + c*t^2 \quad (1)$$

Henderson and Pabis drying model

$$MR = a*\exp(-kt) \quad (2)$$

Where M_i is the observed moisture content and M_{pre} is the predicted moisture contents fitted with drying model and N is the number of observations. The model with higher correlation coefficient and lower standard error and mean relatives deviation modulus values were chosen as better model describing thin layer drying of the Amla fruit.

$$P = \frac{100}{N}\sum\frac{abs(M_i - M_{pre})}{M_i} \quad (3)$$

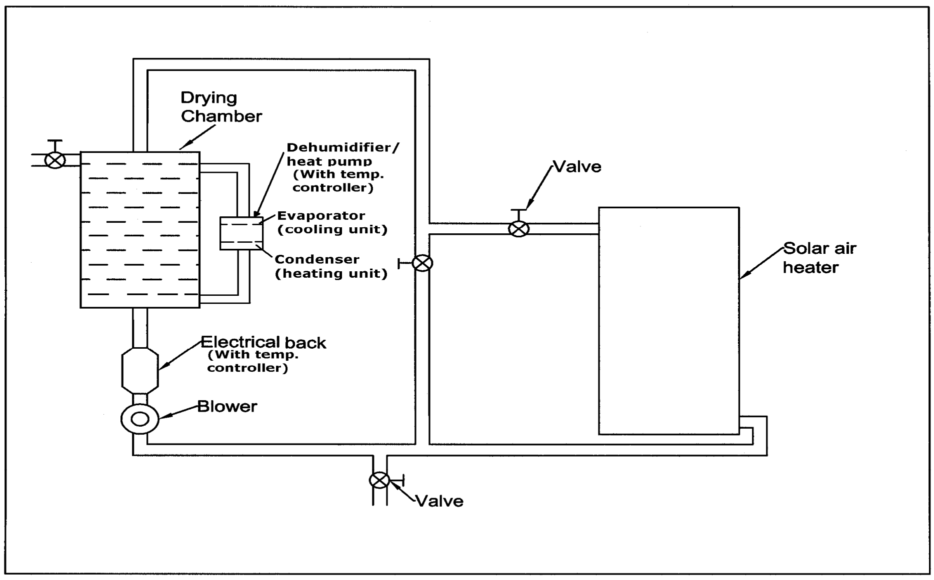

Fig. 1. Schematic of the solar assisted heat pump dryer.

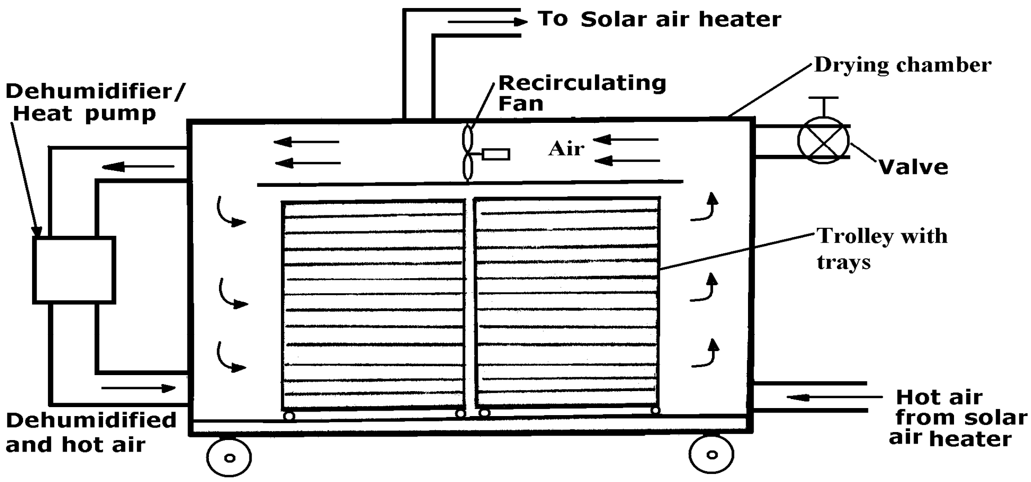

Fig. 2. Schematic of drying chamber.

Table 2. The specifications of the solar assisted heat pump dryer.

Parameters	Details
Drying capacity	20 kg /batch
Dehumidifier	Water removal capacity 1.6 kg/h (at 30°C, 80% RH), 1.6 kW power input
Collector area of solar air heater	2 m^2
Blower capacity	Centrifugal blower, 0.35 kW motor, 200-230 m^3/h air flow
Temperature controller	Micro-processor based temperature controller
Overall size of drying chamber	1700 x 800 x 1500 mm
Drying trays	20 nos.
Tray size	590 x 590 mm with SS wire mesh bottom

2.3 Quality Test of Dried Amla Fruits

The quality of the dried Amla in the heat pump dryer (at different temperature) and in the open sun were measured and compared. Quality parameters (particularly sensitive to heat) such as physical appearance, ascorbic acid (vitamin-C) content, microbial counts were measured. Ascorbic acid was determined by the Johnson method [20]. The microbial count of the dried Amla samples were determined in triplicate as colony forming units/g by spread plate method of sample inoculums [21].

2.3.1 Performance of the Heat Pump Dryer

The coefficient of performance (COP) of the cooling and heating of the heat pump were measured [22]. The $COP_{heating}$ and $COP_{cooling}$ was calculated as per Equation 4 and 5 respectively by dividing the energy output (heat gained by air in condenser or heat taken out for cooling by evaporator calculated as per Equation 6) to work done on the drying system. Total COP of the heat pump was obtained by adding the COP of cooling and heating.

$$COP_{Heating} = \frac{[Q_{\text{Heat released in condensation}}]}{[\text{Work done for heat pump}]} \quad (4)$$

$$COP_{Cooling} = \frac{[Q_{\text{Heat taken out by evaporator}}]}{[\text{Work done for heat pump}]} \quad (5)$$

Heat energy for air cooling/ heating (q)

$$q = m.C_p.\Delta T \quad (6)$$

Where,

m= mass of air flow, kg/s,

C_p = specific heat of air, kcal/kg/°C,

Δ T= temperature difference, °C

The solar air heater adds the heat to the dryer (apart from the condenser of heat pump). The COP of solar air heating system was also obtained by measuring gain of heat energy and electrical energy used in blower [22], [23]. Total COP of the system with solar air heater was also worked out by adding $COP_{(cooling)}$ and $COP_{(heating)}$ of the heat pump. The $COP_{(solar\ heating)}$ was calculated as per Equation 7.

$$COP_{\text{Solar heating}} = \frac{[\text{Energy output by solar air heater}]}{[\text{Electrical energy input to blower}]} \quad (7)$$

The specific moisture extraction rate (SMER) is parameter of the dryer indicate energy effectiveness of the dryer. It is expressed in kg (of water)/kWh. The specific moisture extraction rate (SMER) was calculated as per Equation 8 for a run of drying test [22]:

$$SMER = \frac{[\text{Quantity of the moisture removed}]}{[\text{Energy required for drying}]} \quad (8)$$

Efficiency is also an indicator of effectiveness of the dryer for drying a product. It is expressed in percentage. The dryer efficiency was calculated as per Equation 9 for each run of drying test [22]. The heat energy required for evaporating the water from product was taken as energy out.

$$\text{Dryer efficiency} = \left[\frac{\text{Energy output}}{\text{Energy input to the dryer}}\right] \times 100 \quad (9)$$

The air temperature in the drying chamber was measured with help of the pre-calibrated thermocouples. Energy taken by the heat pump dryer to complete the drying operation was measured with help of the Clamp on Power Meter (Yokogawa CW240). The total solar incident beam radiation was measured with help of the pyranometer (National Instrument Company, India make) on the tilted collector surface. Ambient temperature and humidity were measured with standard wet bulb and dry bulb thermometer and relative humidly was found with help of psychometric chart.

The uncertainties in the measured data were calculated as per the procedure suggested by Moffat [23]. The uncertainty in measurement of temperature, flow rate, oil content, moisture content and time were ±0.5%, ±2.8%, ±1.5%, ±2.0% and ±1.0%, respectively. The uncertainty in experimental efficiency of the solar dryer was ±3%.

3. RESULTS AND DISCUSSION

3.1 Amla Drying in the Heat Pump Dryer and Drying Behaviour

The average weight of the Amla fruit was 23.5 g. The Amla fruit was blanched, deseeded and cut into six pieces before drying. Average thickness of the pieces were 9-10 mm. The average drying time of the Amla in the heat pump dryer from initial moisture content of 88.6% (wb) to about 7.2% (wb) was 50 h, 26 h and 18 h at 35°C, 45°C and 50°C respectively as compared to 8-10 days in the open sun drying. The higher drying time at lower temperature may be attributed to slow migration of the moisture at low temperature. The specific moisture extraction rate and thermal efficiency of the dryer increased with the drying temperature (Table 3). The specific moisture extraction rate was between 0.38-0.45 kg/kWh. The overall thermal efficiency of the dryer was 24-28% (Table 3) as compared to 3.5-4.0% in the open sun drying. The heat pump dryer efficiency obtained was also better as compared to 22% obtained in conventional electrical heated dryer by Das *et al.* [24] for drying potato chips.

The drying models, Henderson and Pabis model and Wang and Singh model were used to describe drying characteristics of the Amla fruit. Correlation coefficient squared (r^2), standard error and mean relative deviation modulus (P) for both models were compared. The Table 4 shows that Henderson and Pabis model obtained r^2 value 0.95-0.99, standard error 6-12 and P values 10.2-15.6% (Table 4), which are in the fairly acceptable range [25]. Wang and Singh model obtained the r^2 value 0.96-0.99, standard error 12-42 and P values in the range 125-1033%, which are not acceptable. Figure 3 depict the Henderson and Pabis drying model curve between drying time and moisture content (db) for the experimental data of the thin layer Amla pieces at

35°C, 45°C and 50°C. The predicted values by Wang and Singh model (at 45°C temperature) also shows significant difference from measured values (Figure 3). Therefore, Henderson and Pabis model was selected in the present study to predict drying characteristics of the Amla fruit.

The coefficients (‘a’ and ‘k’) of the Henderson and Pabis drying model were taken as average value of the three drying constants. The drying model so generated with respect to time (t) at 35°C, 45°C and 50°C are given below:

At 35°C

$$MR = 1.3356 * \exp(-0.0021t) \quad (10)$$

At 45°C

$$MR = 1.7038 * \exp(-0.0041t) \quad (11)$$

At 50°C,

$$MR = 1.516 * \exp(-0.0055t) \quad (12)$$

The coefficient ‘a’ of the Henderson and Pabis model depends upon shape and size of the sample [26]. The values were greater one in all cases. The Amla dried were triangular prism shaped obtained by splitting the whole Amla fruits (average diameter of 26 mm and 23.5 g weight) into six pieces. The value of ‘k’ depends upon the rate of the drying [27]. It was found increasing with the drying temperature. Thus, the drying temperature had significant effect on the rate of Amla drying.

Figure 4 presents the comparison between predicted and actual values of moisture content (db). Good agreement was obtained between predicted and experimental values. The deviation between experimental and predicted correlated data was within ±12% limit.

Table 3. Drying parameters in the heat pump dryer.

Initial moisture content, % (wb)	Final moisture content, % (wb)	Drying temp., °C	Ambient temp., °C	Ambient RH, %	Drying time, h	Electrical energy required, kWh	SMER, kg/ kWh	Dryer efficiency, %
88.6	7.4	35±2	24.4	64	50	23.9 (23.7-24.2)	0.38	24.0
88.6	7.3	45±2	25.2	63	26	26.7 (26.5-26.9)	0.433	26.7
88.6	7.0	50±2	27.8	62	18	27.9 (27.7-28.2)	0.450	27.9

Table 4. Statistical analysis of the models fitted to the drying data for thin layer Amla pieces.

Drying temperature, °C	RH in drying chamber, (%)	*M_e (%)	r^2	S	P (%)	Air circulation rate in drying chamber, m^3/h
Henderson and Pabis model						
35°C	27	7.2	0.99	6.13	10.2	550
45°C	24	6.2	0.95	11.7	15.6	550
50°C	20	5.7	0.98	8.07	14.9	550
Wang and Singh model						
35°C	27	7.2	0.96	34.1	865	550
45°C	24	6.2	0.98	12.0	125	550
50°C	20	5.7	0.99	42.2	1033	550

*Source: [16]

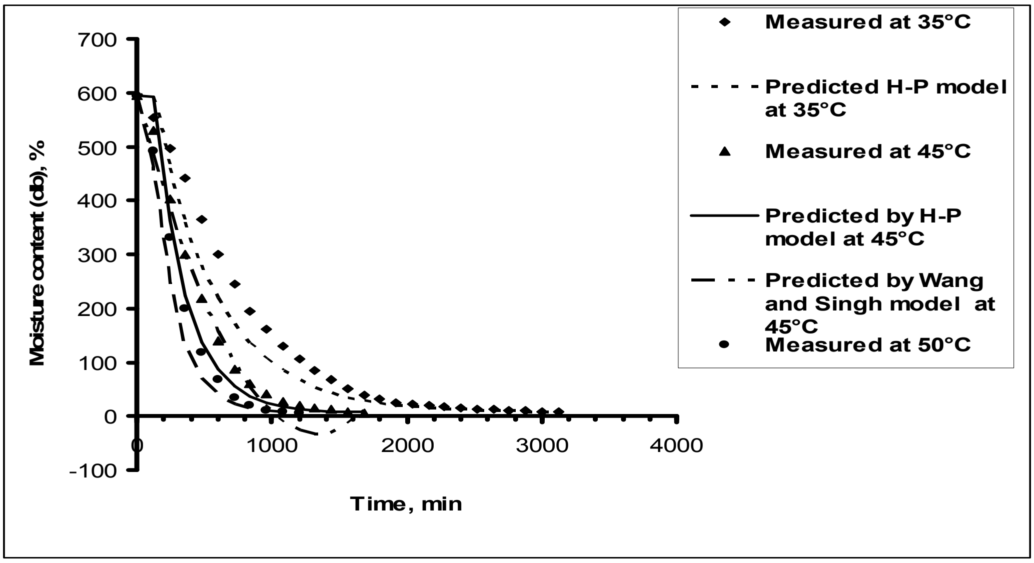

Fig. 3. Moisture content of the Amla predicted during drying from Henderson and Pabis model, Wang and Singh model and measured experimental data.

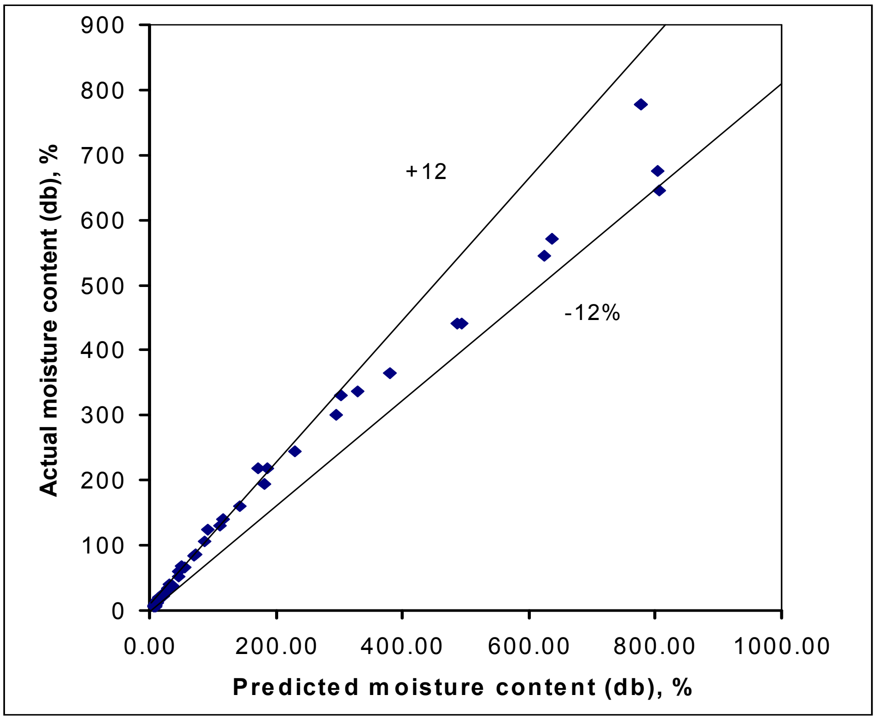

Fig. 4. Comparison of actual and predicted moisture content by Henderson and Pabis model.

3.2 Quality of the Dried Amla Fruits

Physical appearance of the dried Amla in the heat pump dryer was better as compared the open sun dried Amla. Colour of the Amla dried in the dryer was greenish (at 35°C) and light brownish (at 45-50°C), whereas it was dark brownish in case of open sun drying.

Ascorbic acid (vitamin-C) is sensitive to heat and light. The vitamin-C content in the Amla dried at 35°C, 45°C and 50°C were 486 mg/100 g, 380 mg/100 g, and 324 mg/100 g as compared to 258 mg/100 g in the open sun dried (Table 5). The vitamin-C content was higher at lower drying temperatures. This may be attributed to comparatively less loss of vitamin-C at lower temperature. The vitamin-C content in the heat pump dried Amla was improved up to 88% (at 35°C drying temperature) as compared to the open sun drying. The lower content of vitamin-C in the open sun dried Amla may due to long exposure (8-10 days) to the hot sun.

The microbial counts in the Amla dried in the heat pump dryer was reduced significantly. Microbial counts in the heat pump dryer dried Amla was 14.2-16.3 x 10^2 CFU/g as compared to 61.3 x 10^2 CFU/g in the open sun dried Amla (Table 5). Lower microbial count in the dryer dried Amla may be attributed to conditions not favourable for the micro-organism and reduced drying time.

3.3 Coefficient of Performance (COP) of the Heat Pump Dryer

The average value of the $COP_{(cooling)}$ and $COP_{(heating)}$ of the heat pump (dehumidifier) were 1.91 and 2.92 respectively. Thus, total average COP (heating and cooling) of the heat pump was 4.83. The COP was improved with solar air heating system. Figure 4 shows variation in cumulative COP of the heat pump with solar air heating system against solar radiation. The COP was increased with the solar intensity. The average COP of the heat pump along with the solar heating system was improved to 6.65 from the 4.83 (without solar heating system).

3.4 Energy Reduction in Drying With Solar Heating Assistance

Solar assistance required during heat pump drying was analysed by measuring the energy required for drying the product without solar assistance and with solar assistance. The solar energy supplementation was available for 7-8 h only during day time, whereas the drying operation was continued until the product dried during off sun shine also. The energy supplementation due to solar assistance was increased with drying temperature. Up to 10% saving in electrical energy was observed due to solar assistance at 50°C drying temperature (Table 6). However, the solar heating assistance was limited to 1.0-1.5% at 35°C drying temperature. At 35°C, most of the heat energy required by dryer was met with the heat released from the condenser of the heat pump. This may be attributed to comparatively lower rate of heat loss from the drying chamber and slow rate of the latent heat required for moisture evaporation at lower drying temperature.

Table 6. Energy reduction of heat pump dryer with solar heating assistance for Amla drying.

Drying temp., °C	Ambient temp., °C	Total energy taken for drying, kWh		Energy reduction by solar assistance (%)
		Heat pump	Solar heating assistance	
35±2	24.4	32.5-33.2	32.6-32.9	1.0-1.5
45±2	25.2	29.4-29.7	26.8-27.2	7.0-7.5
50±2	27.8	28.2-28.6	25.4-25.8	9.5-10.0

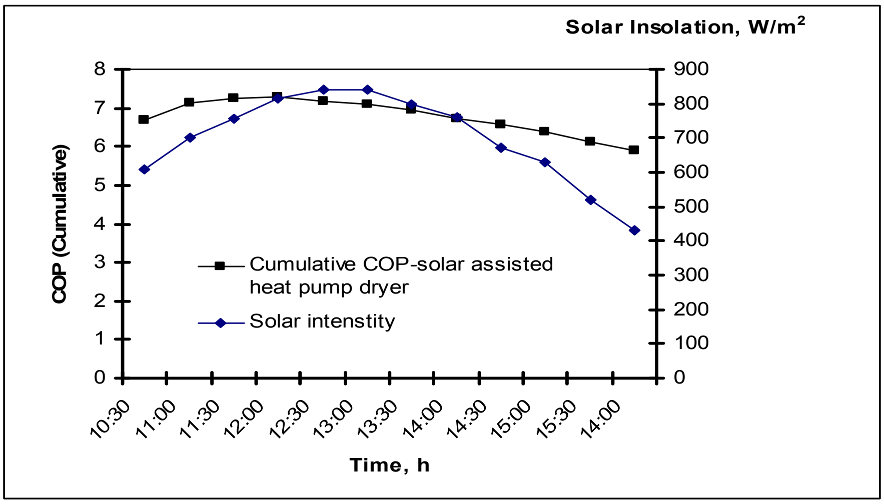

Fig. 5. The cumulative COP of heat pump along with solar air heating system during the day (COP of heat pump: 4.83, Solar collector area= 2.0 m^2, electrical energy input to blower= 0.20 kW, ambient temperature= 25-28°C).

4. CONCLUSIONS

The blanched and deseeded Amla fruit was dried in a solar assisted heat pump dryer (20 kg/batch capacity). The vitamin-C content in the heat pump dried Amla was improved up to 88% as compared to the open sun drying. There was significant reduction in microbial counts in the Amla dried in the heat pump dryer. The drying time of Amla from initial moisture content of 88.6% (wb) to about 7% (wb) was 50 h at 35°C, 26 h at 45°C and 18 h at 50°C as compared to 8-10 days in the open sun drying. Drying behaviour of the Amla fruit best fitted with the Henderson and Pabis thin layer drying model. The total COP (heating and cooling) of the heat pump was 4.8. Along with the solar air heating system, the COP was improved to 6.6. Thermal efficiency of the dryer was 24-28% for Amla fruit drying.

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NOMENCLATURE

MR	$= \frac{M - M_e}{M_o - M_e}$ = moisture ratio
SMER	= specific moisture extraction rate
COP	= coefficient of performance
m_w	= mass water evaporated from Amla during drying, kg
L_w	= latent heat of evaporation of water, kJ/kg
I	= total incident solar radiation on the tilted collector surface, kW/m^2
A	= solar collector area, m^2
Δ T	= temperature difference, °C
RH	= relative humidity
k	= drying constant, min^{-1}
a, b, c	= model coefficients
t	= time, min
db	= dry basis
wb	= wet basis
S	= standard error
r^2	= squared correlation coefficient
P	= mean relative deviation modulus
M_i	= observed moisture content, % db
M_{pre}	= predicted moisture contents, % db
M_e	= equilibrium moisture content, % db
N	= number of observations,
d	= deviation from the mean

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