DEVELOPMENT OF SOLAR-CUM-BIOMASS ENERGY HYBRID DRYER FOR SIMAROUBA LEAVES

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in

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BENGALURU **NOVEMBER, 2020**

Affectionately
Dedicated
to
My Beloved Family &
Special one – "Betu"

**DEPARTMENT OF AGRICULTURAL ENGINEERING,
UNIVERSITY OF AGRICULTURAL SCIENCES
BANGALORE**

CERTIFICATE

This is to certify that the thesis entitled **"DEVELOPMENT OF SOLAR-CUM-BIOMASS ENERGY HYBRID DRYER FOR SIMAROUBA LEAVES"** submitted in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY (Agricultural Engineering)** in **PROCESSING AND FOOD ENGINEERING** to the University of Agricultural Sciences, Bangalore, is a record of *bona-fide* research work carried out by **Mr. BHUVA SACHIN SANATKUMAR,** ID No. **PALB 8365** under my guidance and supervision. The thesis has not previously formed the basis for the award of any degree, diploma, associate-ship, fellowship or other similar titles.

Bengaluru
November, 2020

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DEVELOPMENT OF SOLAR-CUM-BIOMASS ENERGY HYBRID DRYER FOR SIMAROUBA LEAVES

BHUVA SACHIN SANATKUMAR

ABSTRACT

Solar-cum-biomass energy hybrid dryer, an integration of both solar and biomass energy dryer was developed for bulk drying of simarouba leaves especially in non-electrified areas. The major components of the dryer are drying chamber, solar energy collection chamber and heat exchanging unit. Glazing materials (Acrylic sheet, Ethylene vinyl alcohol film, Fibre glass, Polyethylene film, Polycarbonate sheet and Polyvinyl chloride sheet) for effective harness of solar energy was selected based on an effective temperature profile inside the solar energy collection chamber. Polycarbonate sheet was found to be best due to its high temperature profile, average maximum temperature of 43.1 ^{o}C and average daily temperature of 38.4 ^{o}C. Drying of simarouba leaves using hybrid dryer was carried out and compared with sun drying, shade drying, tray drying, solar drying and biomass drying methods. Leaf moisture content was reduced approximately from 64% to 10% in all drying methods. Drying period in hybrid drying (20 h) was found to be shorter as compared to sun (32 h), shade (56 h) and solar drying (34 h). Fuel requirement for combustion of briquette for energy source was found 33% lower for hybrid dryer as compared to biomass dryer. Total cost of hybrid dryer was lower as compared to tray dryer of the same capacity. Simarouba leaves dried under hybrid dryer retained about 74.65% and 76.84% of total phenols and total flavonoids, respectively as compared to fresh leaves. Therefore, solar-cum-biomass energy hybrid dryer would be cost effective and well suitable to dry simarouba leaves in non-electrified areas.

November, 2020

Department of Agricultural Engineering, UAS, Bangalore

Darshan M. B.
Chairperson

ಸಿಮರೋಬಾ ಎಲೆಗಳಿಗಾಗಿ ಸೌರ ಮತ್ತು ಬಯೋಮಾಸ್ ಶಕ್ತಿಯಾಧಾರಿತ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್ ಅಭಿವೃದ್ಧಿ

ಭುವ ಸಚಿನ್ ಸನತ್ಕುಮಾರ್

ಅಮೂರ್ತ

ವಿದ್ಯುದ್ದೀಕರಿಸದ ಪ್ರದೇಶಗಳಲ್ಲಿ ಸಿಮರೋಬಾ ಎಲೆಗಳನ್ನು ಬೃಹತಾಗಿ ಒಣಗಿಸಲು ಸೋಲಾರ್ ಮತ್ತು ಬಯೋಮಾಸ್ ಶಕ್ತಿಯಾಧಾರಿತ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್ ಅನ್ನು ಅಭಿವೃದ್ಧಿಪಡಿಸಲಾಯಿತು. ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್ನ ಪ್ರಮುಖ ಭಾಗಗಳೆಂದರೆ ಒಣಗಿಸುವ ಛೆಂಬರ್, ಸೌರಶಕ್ತಿ ಸಂಗ್ರಹಿಸುವ ಛೆಂಬರ್ ಹಾಗು ಶಾಖ ವಿನಿಮಯ ಘಟಕ. ಸೌರ ಶಕ್ತಿಯ ಪರಿಣಾಮಕಾರಿ ಸರಂಜಾಮುಗಾಗಿ ಸೌರ ಶಕ್ತಿ ಸಂಗ್ರಹ ಛೆಂಬರ್ನ ಪರಿಣಾಮಕಾರಿ ತಾಪಮಾನದ ಪ್ರೊಫೈಲ್ ಆಧರಿಸಿ ಗ್ಲೇಸಿಂಗ್ ವಸ್ತುಗಳನ್ನು (ಅಕ್ರಿಲಿಕ್ ಶೀಟ್, ಎಥಿಲೀನ್ ವಿನೈಲ್ ಆಲ್ಕೋಹಾಲ್ ಫಿಲ್ಮ್, ಫೈಬರ್ ಗ್ಲಾಸ್, ಪಾಲಿಯೆಥಿಲೀನ್ ಫಿಲ್ಮ್, ಪಾಲಿಕಾರ್ಬೋನೇಟ್ ಶೀಟ್ ಮತ್ತು ಪಾಲಿವಿನೈಲ್ ಕ್ಲೋರೈಡ್ ಶೀಟ್) ಆಯ್ಕೆಮಾಡಲಾಯಿತು. ಅಧಿಕ ತಾಪಮಾನದ ಪ್ರೊಫೈಲ್ ಆದ ೪೩.೧ ^{0}C ಸರಾಸರಿ ಗರಿಷ್ಠ ತಾಪಮಾನ ಮತ್ತು ೩೮.೪ ^{0}C ಸರಾಸರಿ ದೈನಂದಿನ ತಾಪಮಾನದ ಅನುಸಾರ ಗ್ಲೇಸಿಂಗ್ ವಸ್ತುಗಳಲ್ಲಿ ಪಾಲಿಕಾರ್ಬೋನೇಟ್ ಶೀಟ್ ಉತ್ತಮವಾಗಿ ಕಂಡುಬಂದಿದೆ. ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್ನಲ್ಲಿ ಸಿಮರೋಬಾ ಎಲೆಗಳನ್ನು ಒಣಗಿಸಲಾಯಿತು ಹಾಗು ಸನ್ ಡ್ರೈಯಿಂಗ್, ಶೇಡ್ ಡ್ರೈಯಿಂಗ್, ಟ್ರೇ ಡ್ರೈಯಿಂಗ್, ಸೋಲಾರ್ ಡ್ರೈಯಿಂಗ್ ಮತ್ತು ಬಯೋಮಾಸ್ ಡ್ರೈಯಿಂಗ್ ವಿಧಾನಗಳಿಗೆ ಹೋಲಿಸಲಾಯಿತು. ಎಲ್ಲಾ ಒಣಗಿಸುವ ವಿಧಾನಗಳಲ್ಲಿ, ಎಲೆಯ ತೇವಾಂಶವನ್ನು ಅಂದಾಜು ಶೇ. ೬೪ ರಿಂದ ಶೇ. ೧೦ ಕ್ಕೆ ಇಳಿಸಲಾಯಿತು. ಸನ್ ಡ್ರೈಯಿಂಗ್ (೩೨ ಘಂಟೆ), ಶೇಡ್ ಡ್ರೈಯಿಂಗ್ (೫೬ ಘಂಟೆ) ಮತ್ತು ಸೋಲಾರ್ ಡ್ರೈಯಿಂಗ್ (೩೪ ಘಂಟೆ) ವಿಧಾನಗಳಿಗೆ ಹೋಲಿಸಿದರೆ ಒಣಗಿಸುವ ಅವಧಿ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯಿಂಗ್ (೨೦ ಘಂಟೆ) ವಿಧಾನದಲ್ಲಿ ಕಡಿಮೆ ಎಂದು ಕಂಡುಬಂದಿದೆ. ಬ್ರಿಕ್ವೆಟ್ ಅನ್ನು ಶಕ್ತಿಯ ಮೂಲವಾಗಿ ದಹಿಸಿ, ಬಯೋಮಾಸ್ ಡ್ರೈಯರ್‌ಗೆ ಹೋಲಿಸಿದಾಗ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್‌ಗೆ ಶೇ. ೩೩ ರಷ್ಟು ಇಂಧನದ ಅವಶ್ಯಕತೆಯು ಕಡಿಮೆ ಎಂದು ಕಂಡುಬಂದಿದೆ. ಸಮ ಸಾಮರ್ಥ್ಯವುಳ್ಳ ಟ್ರೇ ಡ್ರೈಯರ್‌ಗೆ ಹೋಲಿಸಿದರೆ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್‌ನ ಒಟ್ಟು ವೆಚ್ಚವು ಕಡಿಮೆಯಾಗಿರುತ್ತದೆ. ತಾಜಾ ಎಲೆಗಳಿಗೆ ಹೋಲಿಸಿದಾಗ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯಿಂಗ್ ವಿಧಾನದಲ್ಲಿ ಒಣಗಿದ ಸಿಮರೋಬಾ ಎಲೆಗಳಲ್ಲಿ ಶೇ. ೭೪.೬೫ ರಷ್ಟು ಒಟ್ಟು ಫೀನಾಲ್ಗಳು ಹಾಗು ಶೇ. ೭೬.೮೪ ರಷ್ಟು ಒಟ್ಟು ಫ್ಲೇವನಾಯ್ಡ್‌ಗಳು ಉಳಿದಿರುವುದಾಗಿ ಕಂಡುಬಂದಿದೆ. ಆದ್ದರಿಂದ, ಸೋಲಾರ್ ಮತ್ತು ಬಯೋಮಾಸ್ ಶಕ್ತಿಯಾಧಾರಿತ ಹೈಬ್ರಿಡ್ ಡ್ರೈಯರ್ ಸಿಮರೋಬಾ ಎಲೆಗಳನ್ನು ಒಣಗಿಸಲು ವೆಚ್ಚ ಪರಿಣಾಮಕಾರಿಯಾಗಿದೆ ಹಾಗು ವಿದ್ಯುದ್ದೀಕರಿಸದ ಪ್ರದೇಶಗಳಿಗೆ ಸೂಕ್ತವಾಗಿರುತ್ತದೆ.

ನವಂಬರ್, ೨೦೨೦

ಕೃಷಿ ಎಂಜಿನಿಯರಿಂಗ್ ವಿಭಾಗ

ಕೃಷಿ ವಿಶ್ವವಿದ್ಯಾನಿಲಯ, ಬೆಂಗಳೂರು

ದರ್ಶನ್ ಎಂ. ಬಿ.

ಮುಖ್ಯ ಸಲಹೆಗಾರರು

"DEVELOPMENT OF SOLAR-CUM-BIOMASS ENERGY HYBRID DRYER"

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INTRODUCTION

- The objective of drying is to reduce the moisture up to safe storage level, which also facilitates processing, packaging and transportation.
- India has a great solar energy potential of 4-7 kWh/m^2 per day and huge amount of biomass production from agricultural waste and by-products.
- Solar drying is the efficient replacement of disadvantages in traditional open-sun drying, for higher performance and good quality of product.
- Direct type passive solar dryers performed higher, as direct exposer without any external energy sources, for small batches of food stuffs (Sanusi *et al.*, 2013).
- Glass, plastic films and rigid panels are used for the greenhouse/solar type dryer in order to heat the drying air.
- Drying chamber of 1 m * 1 m * 1 m with polycarbonate as a cover gave a high-quality dried rubber with 10 °C more inside temperature than ambient air (Arekornchee *et al.*, 2014).
- The use of biomass as heating sources with solar dryer improves the efficiency of agricultural dryers. Rice husk, wheat straw etc. and modified forms (Briquettes) are easily and readily available for gasification.
- During winter and monsoon, drying could be compensated by biomass heat back up in cold or cloudy days for efficient performance of dryer.

OBJECTIVES

The objectives of the study is:

1. Selection of covering material for direct passive drying.
2. Development of Solar-cum-Biomass Energy Hybrid Dryer.

MATERIALS AND METHODS

- Six different types of covering materials *viz.* Polyethylene film, Ethylene vinyl alcohol (EVOH) film, Poly-vinyl Chloride (PVC) sheet, Acrylic sheet, Fibre glass and Polycarbonate sheet were compared for covering material using One-way ANOVA.
- Temperature of top, centre and bottom inside the chambers were recorded with digital temperature indicator (Make: Beltronics).
- Temperature profile inside the chambers along with ambient air temperature were observed during bright sunny days (09:00 a.m. to 05:00 p.m.) of February, 2020 at UAS, Bangalore.
- Relative humidity of the ambient air and inside atmosphere of the chambers were observed using humidity sensor in order to relate with temperature profile.
- Solar-cum-Biomass Energy Hybrid Dryer was designed and fabricated at Workshop, AICRP on PHET, UAS, Bangalore.
- Total energy to remove the moisture (Kishore *et.al.*, 2014):

$$Q_n = W_t \times C_p \times (T_d - T_a) + M_w \times \lambda$$

Where, W_t = Mass of the wet product, kg; C_p = Specific heat of product, kJ/kg.°C; T_d = Drying temperature, °C; T_a = Ambient temperature, °C; M_w = Mass of the water removed, kg; λ = Latent heat of vaporization of water, kJ/kg

- Materials for fabrication *viz.* MS sheets, MS angle bars, aluminium perforated sheets were purchased from local markets of Bangalore.
- **Different parts of the dryer:**
  - i. Solar energy collection chamber:
    Cubic shaped 80 cm * 80 cm * 80 cm in dimensions with 5 sides covered with polycarbonate sheet.
  - ii. Drying chamber:
    Aluminium perforated sheet shaped in open top cylinder with height of 80 cm and 60 cm diameter. Central exhaust provision with same height and 12 cm diameter was made.
  - iii. Biomass energy heat exchanger:
    Shell and Duct type heat exchanger made up of MS sheet was installed at the bottom of solar drying unit.
    Shell: 80 cm * 80 cm * 62.6 cm
    Duct: Cross section - 18 cm * 18 cm & approx. length of 322 cm.
  - iv. Frame
    To connect biomass and solar unit and to support the drying unit.

RESULTS

- The measured thickness of polyethylene and EVOH films were 0.12 mm, whereas fibre glass and PVC sheets were 1 mm thick, while acrylic and polycarbonate sheets were 1.72 mm and 3.73 mm in thickness, respectively.
- Highest, 43.1 °C temperature was recorded for polycarbonate covered chamber at 01:00 p.m. noon for an average daily temperature of 38.4 °C.
- Approximated cost of the dryer was Rs. 27,395.

Covering Material	Average Daily Temperature, °C	Average Daily Humidity (Rh), %
Ambient air	31.3	37.5
Polyethylene	35.0	34.1
Polycarbonate	38.4	25.5
EVOH	35.1	32.4
PVC	35.5	30.4
Fibre Glass	36.7	27.6
Acrylic	35.7	28.9
S.Em±	1.01	1.12
CD at 5%	NS	3.46
C.V.	0.05	0.07

Table 1: Avg. temp. & Rh inside chambers (Feb., 2020)

Material	Size	Nos.
Drying Chamber		
Aluminium perforated sheet	1.88 * 0.8 m	1 piece
Aluminium perforated sheet	0.4 * 0.8 m	1 piece
Aluminium perforated sheet	0.6 m dia.	1 piece
Solar Energy Collection Chamber		
MS angle bar	0.8 m	12 pieces
Polycarbonate sheet	0.8 * 0.8 m	5 pieces
Biomass heat energy exchange system		
Shell		
MS sheet, 18 gauge	0.626 * 0.8 m	4 pieces
MS sheet, 18 gauge	0.8 * 0.8 m	2 pieces
Duct		
MS sheet, 18 gauge	1.2 * 2.4 m	2 pieces
Frame		
MS angle bar	1 m	14 pieces
MS sheet, 16 gauge	1 * 1 m	1 piece

Table2 : Materials used for dryer with dimensions

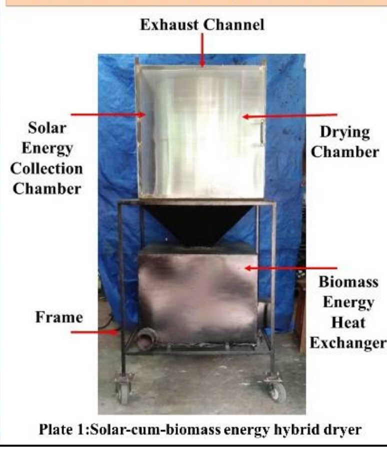

Plate 1:Solar-cum-biomass energy hybrid dryer

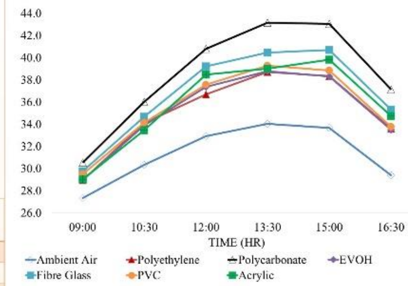

Figure 1: Temperature, °C profile inside chambers

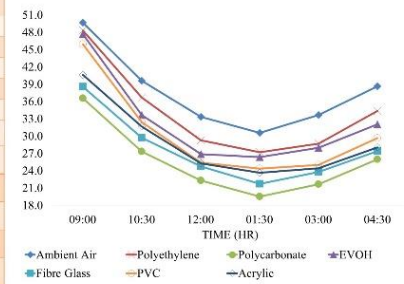

Figure 2: Relative Humidity (Rh),% inside chambers

DISCUSSION

- Polycarbonate sheet observed better average temperature difference of 7.2 °C per day as compared to others. With higher thickness, it gives higher strength.
- 5 to 9 °C higher temperature of drying air was reported as compared to ambient air for polyethylene covered drying chamber during operation (Koyuncu, 2006).
- Lower the relative humidity of air, higher the moisture absorption capacity of the air. Ambient air humidity was 12.0% lower than polycarbonate covered atmosphere.
- Biomass unit would be used by attaching furnace in order to compensate energy requirement.
- Study was attempted for low cost dryer with suitability at farm level which was obtained.

SUMMARY

- Polycarbonate covered atmosphere was reported for higher temperature difference (7.2 °C) with ambient air.
- Relative humidity observed lower in all cases and lowest 25.5% was for polycarbonate covered chamber.
- The overall dimensions of dryer was 2.3 m * 1 m * 1 m.

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Abbreviations / Symbols	Description
AIDS	Acquired Immunodeficiency Syndrome
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
C.V.	Coefficient of Variance
CAD	Computer Aided Design
CD	Critical Difference
CFD	Computational Fluid Dynamics
cm	Centimeter
cm^2	Square centimetre
d.b	Dry basis
DPPH	2, 2- Diphenyl-1-picrylhydrazyl
EFB	Empty Fruit Bench
et al.	And others
etc.	Etcetera
EUR	Energy Utilization Ratio
EVOH	Ethylene Vinyl Alcohol
FCR	Folin Ciocalteu Reagent
g	Gram
GAE	Gallic Acid Equivalents
h	Hour/s
HIV	Human Immunodeficiency Virus
HUF	Heat Utilization Factor

IC	Inhibitory Concentration
ICRAF	International Council for Research in Agroforestry
IEA	International Energy Agency
kg	Kilogram
kJ	Kilo joule
kWh	Kilo-watt hour
LPG	Liquefied Petroleum Gas
m	Meter
m^2	Square meter
m^3	Cubic meter
mg	Milligram
MJ	Megajoules
ml	Milli liter
mm	Milli meter
MNRE	Ministry of New and Renewable Energy
MT	Million tonnes
MW	Mega watt
N	Normal
$NaNO_2$	Sodium Nitrite
NaOH	Sodium Hydroxide
nm	Nano meter
NS	Not significant
OD	Optical Density
ppm	Parts per million

PVC	Polyvinyl Chloride
RDA	Recommended Dietary Allowance
Rh	Relative humidity
Rs.	Rupees
s	Second/s
SEM	Standard error of mean
Std.	Standard
UV	Ultra-violet
viz.	Namely
W	Watt
w.b.	Wet basis
&	And
^{o}	Degree
^{o}C	Degree Celsius
=	Equal to
µg	Microgram
×	Multiply
/	Per
%	Per cent
+	Plus
±	Plus or minus

I INTRODUCTION

Simarouba (*Simarouba glauca*), also known as ‘Paradise tree’, belongs to family *Simaroubaceae*. It is known as ‘Laxmitaru’ in Kannada language. *Glauca* is a species, whose name comes from ‘*glaukos*’ (Greek) which means covered with the bloom of bluish green foliage. It is indigenous to Southern Florida, the West Indies and Brazil. Bahamas, Costa Rica, Cuba, EI-Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Puerto Rico and United States of America are also native of simarouba. It is outlandish tree for India, Myanmar, Philippines and Srilanka (Manasa *et al.*, 2019). In India, simarouba was first introduced at Research Station of Amravati, Maharashtra in the year of 1966 by ICAR - National Bureau of Plant Genetic Resources, New Delhi for edible oil purpose. Later, it was introduced at University of Agricultural Sciences, Bangalore in 1986. Now a day, it is one of the major oil seed trees which have been spread across different states of India like Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Orissa, Rajasthan, Tamil Nadu and West Bengal.

Simarouba grows at height of 12-15 m with stem of up to 9 m height and 40-50 cm diameter. It is evergreen tree with large circular crown (Molina *et al.*, 1996). It produces bright green leaves, small white flowers and small red coloured fruits. Leaves are compounded with 3-21 oblong shaped leaflets and notched or smooth at apex. Leaflets are alternate, even and bluish oily green in colour. Besides the oil extraction from the seeds of simarouba, other parts of tree such as leaves and bark are very useful in the field of traditional medicine. The leaves and bark of simarouba contain quassinoids which are the chemicals belong the group of triterpenes. Quassinoids have inhibitory, anti-inflammatory and antiproliferative effects on tumor cells. Natural quassinoids are the promising source of small molecules for the generation of more active compounds for development of anticancer agents which is less toxic (Ramya *et al.*, 2018).

Simarouba leaves are rich source of important phytochemicals such as phenols, flavonoids and antioxidants. They possess analgesic, antimicrobial, antiviral, astringent, emmenagogue, stomachic, tonic and vermifuge properties. These leaves are used in the treatment of colitis, diarrhoea, dysentery, malaria, skin affections and intestinal worms.

Infusion of the leaves and bark is considered to be astringent, an antiparasitic remedy and also used in stimulation of digestion and menstruation. The healing potential of simarouba has been established by animal studies, thus it is used to heal wounds and sores. Phytochemicals from dry leaves of simarouba are extracted using either hot water (Manasa *et al.*, 2019) or organic solvents like ethanol and methanol (Jangale *et al*., 2012). Drying of simarouba leaves is essential prior to extraction of phytochemicals.

Drying is a process of heat and mass transfer in which water is removed due to vapour pressure gradient. In drying, higher temperature helps in increasing the vapour pressure of the product, thus leading to faster and efficient moisture removal. The reduction in moisture level helps safe storage of agricultural products. Drying also reduces volume and weight substantially with minimising costs of packaging, transportation and storage (Okos *et al.*, 1992). However, it effects greatly on the quality of the dried products. The different drying methods used for agricultural crops are sun drying, solar drying, biomass drying, shade drying, hot air drying, vacuum drying, freeze drying, etc. Drying requires about 40–50% of the total energy required for production and processing of agricultural products. The present climatological and economic situation of the country demands an eco-friendly and cheap source of energy for the drying. In non-electrified rural areas, drying of agricultural products using solar or biomass as energy sources are preferred due to unavailability of electricity and expensive fossil fuels. Solar and biomass energies are freely and abundantly available to the rural population. Ministry of New and Renewable Energy (MNRE), Government of India had targeted to achieve 10,100 MW from solar energy and 407.50 MW from biomass energy for the year 2017-18, however, 1715.82 MW and 10.50 MW, respectively, had been harnessed at the end of August 31st, 2017 (MNRE, 2017). As a contribution to the set target, there is a scope for developing renewable based agricultural processing machineries.

Solar energy is an important alternative energy source which is preferred now-a-days for drying of agricultural produces. It is abundant, inexhaustible and non-pollutant. Further, it is renewable, cheap and environmentally friendly. Solar energy can be utilised directly through open sun drying or solar drying systems. Open sun drying is a conventional method which utilises direct solar radiation to dry the materials in open condition. Limitations of sun drying are quantitative losses of produce by animals, birds and rodents, degradation in quality due to direct exposure to solar radiation, dew or rain, contamination by dirt, dust or debris. Also, chances of insect infestation and growth of microorganism due to non-uniform drying are more in open sun drying. To overcome these limitations, solar drying using solar tunnel dryers or solar cabinet dryers are preferred over conventional sun drying. The solar drying systems are advancement of sun drying, which dry products in a closed system with higher inside temperature (Rajkumar *et al.*, 2007). Several attempts have been made significantly in recent years for harnessing solar energy for drying. However, unfavourable weather conditions like cloudy and night hours limit the effective solar energy utilization.

Biomass is a residue available as by product of crop production, organic matter from forest and agro or food industrial waste. Primary agricultural residues like paddy straws, sugar cane tops, cotton and other stalks, dry coconut leaves (frond), mulberry stalks, etc. are obtained from the field at the time of pruning and harvest. Secondary residues like husk, bagasse, deseeded maize cobs, coconut shells etc. are by products obtained during processing. Biomass, an abundant renewable energy source, could bring sustainable economic growth in developing countries. Over 90% of households in rural and 15% of households in urban areas use biomass to meet their primary energy requirements. India has a large geographical area under crop cultivation (180 million ha) and produces massive amount of biomass residues (Prasad *et al.*, 2007). It has been estimated that 686 MT of crop residues were generated in India every year, out of which 234 MT (34%) is estimated as surplus for bio-energy production (Hiloidhari *et al.*, 2014). Modern uses of biomass include higher efficiency for heat and power generation through direct biomass combustion, co-firing with coal and biomass gasification (IEA, 2012). In biomass energy dryer, biomass is burnt directly for generation of hot flue gas. Flue gas (smoke) is used to heat the incoming ambient air indirectly with the help of heat exchanger for the production of hot air.

Solar-cum-biomass energy hybrid dryer (Hybrid dryer) is an integration of both solar dryer and biomass fired dryer. The main components are drying chamber and heat exchanger. This dryer utilises direct solar energy for drying the product in upper drying chamber during bright sunshine hours. During night and cloudy hours, bottom unit is used for generation of hot air with the help of heat exchanger. The hybrid dryer integrated with solar and biomass energy gives advantages in enhancing drying efficiency, reduction in losses, control over quality and reduction in operational time. Energy saving techniques with reduction in labour requirement gives economic benefits.

Now-a-days, simarouba leaves are gaining attention in the field of medicine due to their rich phytochemical properties. The presence of pharmacological properties of simarouba leaves helps in curing cancer and diabetes. Dry leaves of simarouba are essential for the extraction of phytochemical rich health decoction. Currently, shade drying is used to obtain dry leaves of simarouba for extraction of health decoction. Shade drying method takes higher time and also leads to deterioration in quality. Quality deterioration also arises in open sun drying. Further, the area required in both shade and sun drying is larger. Drying in closed system is more suitable than open drying for the products which are sensible to photo-oxidation. Though, commercial hot air-drying using tray dryers, vacuum dryers, freeze dryers, etc. is suitable, it is expensive and not feasible in non-electrified area. Therefore, solar or biomass drying in closed system can be the alternative technique to obtain the quality dry products. Hybrid dryers in which solar dryers integrated with biomass energy as backup system are more energy efficient in non-electrified rural areas as compare to solar or biomass dryer. The hybrid dryer could be used in unfavourable weather conditions. Very little work has been reported on development of solar-cum-biomass energy hybrid dryer for effective utilization of both solar and biomass energies in an integrated system. To the best of our knowledge, the drying studies of simarouba leaves using solar-cum-biomass energy hybrid dryer have not been conducted. Therefore, the present study titled "Development of Solar-Cum-Biomass Energy Hybrid Dryer for Simarouba Leaves" has been undertaken focusing on the following objectives.

1. Development of solar-cum-biomass energy hybrid dryer for dehydration of simarouba leaves
2. Studies on drying kinetics of simarouba leaves in solar-cum-biomass energy hybrid dryer

II REVIEW OF LITERATURE

Simarouba (*Simarouba glauca*) is receiving great interest as a promising medicinal herb due to presence of pharmaceutically important quassinoids namely, ailanthinone, canthin, dehydroglaucarubinone, glaucarubine, glaucarubolone, glaucarubinone, holacanthone, melianone, simaroubidin, simarolide, simarubin, simarubolide, sitosterol, tirucalla, etc. (Manasi and Gaikwad, 2011). Dry leaves of simarouba are essential for extraction of phytochemically rich health decoction. Simarouba leaves are required to be dried under closed condition preferably under low temperature to preserve the leaf quality. Although many commercial dryers are available in the market for drying the herbs, these are expensive due to high energy cost and also not suitable for non-electrified areas. Open sun drying and shade drying take longer drying period and also require larger yard area in which the materials are exposed to open atmosphere, thus resulting deterioration in final product quality due to dirt and microbial contamination. Solar dryers are energy efficient, low cost and well suitable for rural areas, however, drying of herbs is not possible during cloudy weather and at night due to their weather dependency. Therefore, the development of solar dryers integrated with biomass could be a better choice for drying the medicinal herbs due to its energy efficacy, low drying cost, improved product quality and suitability in non-electrified areas. Combined solar and biomass dryers would have potential to increase the productivity and resultant economic viability of small and medium-scale enterprises to produce and process agricultural produce in developing countries (Okoroigwe *et al.*, 2013). The design and development of hybrid dryer integrated with solar and biomass energy needs intensive and judicious information on type of materials to be dried, initial moisture, quality and quantity of the materials, energy sources, amount of water to be removed, drying location and its weather condition, etc. Therefore, this chapter deals with the research findings reported by scientists related to simarouba leaves and its properties, drying of medicinal herbs, solar dryers, biomass energy dryers, hybrid dryers, drying models, etc.

2.1 Simarouba Leaves and Its Properties

Simarouba is also known as Aceituno, Bitterwood, Dysentery Bark, Palo Amargo, Paradise Tree, Pitomba, Robleceillo, Simaba and Shorgum Maram. It is an evergreen tree which provides edible oil and used as an herbal medicine in many countries in its long history (Osagie-Eweka *et al*., 2016). All parts of tree *viz.* seed, shell, fruit pulp, leaf, leaf litter, unwanted branches, stem, bark and root generate products that are useful in the production of food, fuel, manure, timber and medicine. The plant has antiseptic, analgesic, antimicrobial, antiviral, astringent, emmenagogue, stomachic, tonic and vermifuge properties which are medically important (Joshi and Joshi, 2002; Santhosh *et al*., 2016). It is also useful in treating amoebiasis, gastritis, ulcers in the alimentary system, diarrhea, chikun gunya and malaria. The pharmacological properties such as anticancer and antiplasmodial are also present in simarouba. The crushed seeds of simarouba are used as antigo against snake bites (Umesh, 2015).

Simarouba leaves have 11 medicinally important quassinoids, which are glaucarubin, quassinoids, ailanthinone, benzoquinone, holacanthone, melianone, simaroubidin, simarolide, simarubin, simarubolide and sitosterol (Sharanya *et al.*, 2016). Simarouba leaf extract has been reported for the presence of alkaloids, flavonoids, cardenolides, glycosides, phenolic compounds, saponins and fixed oils. Simarouba leaves are believed to aid in the battle against different health issues like cancer and diabetes. An anticancer property of simarouba leave helps in curing 1st and 2nd stage of cancer as well as improves the health and life span in case of patients with 3rd and 4th stages (Manasa *et al.*, 2019).

Rivero-Cruz *et al*. (2005) reported that simarouba contained chemicals having cancer-killing properties. Quassinoids, ailanthinone, glaucarubinone, dehydroglaucarubinone and holacanthone were attributed to the antileukemic and anticancer activity.

Valdes *et al*. (2008) studied in-vitro antimicrobial activities of simarouba leaves. Vegetal material was dried in a ventilated incubator at 30°C and subsequently milled into coarse particles for extraction. The extract exhibited the strong inhibitory activity with

IC_{50} values below 3 μg/ml against all tested protozoa (*Trypanosoma b. brucei, Trypanosoma cruzi, Leishmania infantum and Plasmodium falciparum*). The highest activity of the extracts on bacteria, yeasts and dermatophytes was recovered for simarouba against *M. canis* with an IC_{50} of 2 μg/ml.

Rajurkar (2011) investigated the antibacterial activity of ethanol extracts of simarouba leaves. Leaves were washed in water, chopped, air dried for a week at 35- 40 ^{o}C and pulverized in electric grinder prior to alcoholic extraction. The anti-microbial activity was exhibited significantly as compare to the standard drug tetracycline by the ethanolic extract of simarouba. The extracts formed the inhibition zone (cm) of 1.6, 1.4 and 1.3 for bacteria like *B. subtilis, E. coli* and *S. aureus,* respectively, establishing its antibacterial activity.

Jangale *et al.* (2012) tested inhibitory activity of dried and fresh leaves of simarouba exracts (ethanol and methanol) against food borne pathogenic microorganisms (*Staphylococcus aeureus and Escheria coli*) and food spoilage microorganism (*Bacillus Subtilies and Pseudomonas aeurogenosa*). They reported that ethanol and methanol extracts from medicinal plants were effective to inhibit food born spoilage and pathogenic microorganism. The minimum inhibitory concentration ranged from 160 to 10,240 ppm in all the extracts. Result revealed that the leaves extract of *Simarouba glauca* could prove useful in antimicrobial food packaging.

Mikawlrawng *et al*. (2014) analysed the antifungal properties of simarouba leaves against pathogenic fungi. Methanolic and ethanolic extracts of both fresh and oven dried leaves at 35-40 ^{o}C for 3 days are tested and reported that ethanolic extracts of both fresh and dried leaves were more effective. The leaf extracts were more effective against *Aspergillus parasiticus* and *Fusarium oxysporum*. They also reported that methanolic extract of dried leaves were comparatively more effective than fresh leaves extract in case of *Aspergillus parasiticus*.

Sharma and Sriram (2014) investigated the acute oral toxicity and antiulcer profile of the chloroform extract of simarouba leaves in albino rats. Leaves dried at room temperature were used for studies. Under the acute toxicity study, animals were treated with the chloroform extract of simarouba at the dose of 1800 mg/kg for 14 days. Chloroform extract of the leaves of simarouba was confirmed to decrease the acidity and to increase the mucosal defense in gastric area.

Umesh (2015) evaluated the antioxidant activities of simarouba leaves through different in-vitro testing. Powder of leaves dried at room temperature for 2 weeks were used for studies. The results showed a smaller number of flavonoids (0.14 to 0.18%) with 250-400 μg/mg phenolics and 67-200 μg/mg tannin content in various solvent extracts. Leaf extracts showed iron chelation effect and exhibited strong DPPH radical scavenging activity. The methanolic extract exhibited potential antioxidant activity.

John *et al.* (2016) tested the ethanolic and chloroform extract of dry leaves of simarouba against paracetamol induced hepatic damage for the hepatoprotective activity. Results reported that as compare to paracetamol intoxicated group, administration of low and high dose of chloroform and ethanolic extracts of simarouba reduced a change of cells and central vein in the histology of liver. Both chloroform and ethanol extracts of leaves of simarouba reduced the histological changes caused by paracetamol. The hepatoprotective potential of leaf was due to its presence of antioxidant activity.

Kumar *et al.* (2016) compared simple and soxhlet extraction of methanolic and ethanolic extracts of the leaves of simarouba. Leaf extracts from powder of dried leaves were obtained using different extraction and used for testing the presence of secondary metabolites such as alkaloids, flavonoids, phenols, steroids, glycosides, saponins, tannin, steroid, lignin, saponin, anthraquinone and terpenoid. The result revealed that all tested secondary metabolites were present in all the extracts except saponin and anthraquinone.

Santhosh *et al.* (2016) tested the antibacterial and antioxidant activity of crude petroleum ether and ethyl acetate extracts from dried leaves (mechanically dried leaves at 40-50 ^{o}C or 6 hours) of simarouba. Disc diffusion assay was used against the organisms like *Staphylococcus, Salmonella, Bacillus, Klebsiella, Pseudomonas sp.* and *Escherichia coli* for antimicrobial activity. Antioxidant activity was evaluated using total antioxidant assay, hydroxyl radical scavenging assay and 2, 2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity. Result showed that both extracts had significant antioxidant activity in a dose dependent manner. It was found that ethyl acetate extract was more effective than petroleum ether extract.

Varghese *et al.* (2016) conducted the chemical analysis of simarouba and studied its antimicrobial effect on opportunistic pathogens in HIV/AIDS patient. Fresh leaves dried at the room temperature were used for the extraction and the analysis. Total 88 compounds were detected in leaf of simarouba from five different extracts (38 from petroleum ether, 20 from ethyl acetate, 6 from Acetone, 19 from Ethanol and 13 from aqueous). The presence of phenols, flavonoids, tannins, anthocyanides, anthroquinones, saponins, etc. were confirmed. The results of antimicrobial effect showed inhibitory effect on all four microbes by all the extracts due to presence of antioxidants and other bioactive compounds. The extract of simarouba could be an alternative to bring down the opportunistic infections rate in patients with poor immunity, especially in HIV/AIDS patients.

Vasait and Khandare (2017) tested the antibacterial potential of crude leaf extracts of simarouba against gram-positive and gram-negative isolates. Leaves were shade dried at room temperature for 10 days. The plant extract exhibited bactericidal activity against both the test organisms. The extracts exhibited higher zones of inhibition against *E. coli* (13 mm) and *Salmonella paratyphi B* (12 mm).

Prajapati *et al.* (2018) evaluated anti-cancer activities using leaf extract of simarouba on three different leukemic cancer cell lines (K-562, MOLT-3 and KG-a). Extracts were prepared using different solvents (chloroform, petroleum ether, ethyl acetate, n-butanol, methanol and aqueous). Among the various extracts, methanolic extract of simarouba leaves showed significant anticancer activity against MOLT-3 and K-562 as compare to KG-1 cell line. For K-562, MOLT-3 and KG-1.50%, 50% inhibition of viability (IC_{50}) was found to be 74.21, 69.69 and 131.1 µg/ml, respectively.

Sajeeda *et al.* (2019) conducted the comparative study of phytochemical profile and antioxidant property of different parts of simarouba. The leaves, flowers and bark were separately washed thoroughly and shade dried at room temperature for 30–40 days prior to profiling. Bark and leaves extracts exhibited the maximum number of phytochemicals. Maximum hydrogen peroxide scavenging property of 75.85% and 63.13%, respectively, were found in ethanol and methanol extracts of the leaves at 100 μg/ml with corresponding IC_{50} value of 44.17 μg/ml and 48.29 μg/ml. The ethanol and methanol extracts of leaves showed reducing power of 79.44% and 61.16%, respectively, with IC_{50} values of 43.50 μg/ml and 46.33 μg/ml.

2.2 Drying of Medicinal Herbs

Drying is the most common and fundamental method for post-harvest preservation of medicinal plants because it allows quick conservation of the medicinal qualities of the plant material in an uncomplicated manner. Herbal and medicinal plants in India are dried using traditional method of sun drying resulting poor quality dried products in terms of medicinal qualities. The medicinal qualities are sensitive to methods of drying and drying air temperature. However, factors such as scale of production, availability of new technologies and pharmaceutical quality standards must be considered for medicinal plant drying in modern times.

Yiljep *et al.* (2005) conducted series of experiments on ginger drying. Four processing treatments: whole unpeeled, split-unpeeled, whole-peeled and split-peeled and four drying methods: sun, solar, natural air and fire-heat drying were investigated on their effects on the appearance, aroma/flavour, pungency and the ginger oil/oleoresin yield of dried ginger. Whole-unpeeled samples sufficiently dried by fire-heat drying had given smoky-burnt aroma and a pronounced pungent smell. The analysis of the ginger oil/oleoresin contents in the four treatment samples showed that the highest yield of 2.0% would from the whole-unpeeled samples dried by fire-heat drying. The fire-heat drying of whole-unpeeled ginger would reduce the quality deterioration and may help to alleviate farmers from the high labour-intensive operations of peeling, slicing and sun drying.

Doymaz *et al.* (2006) studied the drying characteristics of dill and parsley leaves. The drying operation was carried out at constant air velocity of 1.1 m/s and temperature of 50, 60 and 70 ^{o}C. The colour values of leaves dried at different temperatures were analysed. L* and b* values were increased where as a* value was decreased with increase in temperature. Further increase in temperature showed adverse effect on colour of dried product. The recommended temperature for the drying of leaves was 60 ^{o}C and drying process was occurred in falling rate region.

Arabhosseini *et al.* (2006) reported the effect of storage on the essential oil content and colour of French Tarragon (*Artemisia dracunculus* L.) leaves. Tarragon leaves were dried at different temperature and relative humidity combinations (45 ^{o}C at 17% Rh, 60 ^{o}C at 7% Rh, 60 ^{o}C at 18% Rh and 90 ^{o}C at 2.5% Rh) and constant air velocity of 0.6 m/s. Oil content and colour values were measured for the fresh and dried leaves immediately after drying as well as after storage of 15, 30, 60 and 120 days. The reduction in oil content and change in colour values were observed during the storage. About 50% reduction in essential oil content and maximum colour change was observed after 30 days for the leaves dried at 90 ^{o}C. These changes were minimum for the leaves dried at 45 ^{o}C.

Ahmet and Orhan (2009) studied the drying kinetics of herbal leaves (nettle and mint) for thin layer drying characteristics in a convective dryer. The observations showed that increase in velocity of drying air from 0.2 m/s to 0.4 m/s and 0.4 m/s to 0.6 m/s, the drying time for nettle and mint leaves decrease by approximately 3% and 7%, respectively, in reference to 280 min at 0.2 m/s velocity. The total drying time for herbal leaves decreased with increase in drying temperature.

Arabhosseini *et al.* (2011) investigated the effect of drying on the colour change in tarragon (*Artemisia dracunculus L.*) leaves. The drying was carried out at 40 to 90 ^{o}C with constant flowrate. The smallest change in L*, a* and b* colour parameters were observed at low temperature and high temperature. At higher temperature, exposer time was less which affected the colour change. The rate of colour change decreased with decrease in moisture content. Matured leaves were less sensitive to temperature than young leaves. Drying of tarragon leaves below 50 ^{o}C was recommended to avoid colour degradation.

Mishra *et al.* (2012) reported the drying data for processing of *Moringa oleifera* leaves for human consumption. Higher Vitamin A content was retained in shade drying (50-70%) as compared to sun drying (20-40%). The leaves could be dried completely within 4 days with loading density of 1 kg per square meter.

Kenghe *et al.* (2015) evaluated quality characteristic of curry leaves dried using different drying methods *viz.* sun drying, shade drying and tray drying (Temperature: 45, 55 and 65 ^{o}C). The observed time required for tray drying was 27% less as compared to sun and shade drying. Curry leaves dried at 55 ^{o}C in tray drying had more porous and uniform structure and also maintained nutritional constituents up to acceptable limit with superior green colour.

Garti *et al.* (2018) studied the effects of shade and sun drying for preservation and retention of nutrients of a leafy vegetable *Hibiscus cannabinus* cultivated at Northern region of Ghana. The drying time was 72 h for both the treatments. Ash, protein, fat, fibre and carbohydrate contents of shade dried leaves were 1.75 ± 0.35 g/100g, 2.56 ± 0.03 g/100g, 0.78 ± 0.06 g/100g, 1.68 ± 0.07 g/100g, 7.38 ± 0.12 g/100g, respectively, and for sun dried leaves were 6.91 ± 0.06 g/100g, 19.14 ± 0.09 g/100g, 4.12 ± 0.04 g/100g, 12.19 ± 0.07 g/100g, 49.16 ± 0.17 g/100g, respectively. Sun dried leaves provided more of Recommended Dietary Allowance (RDA) of fibre, carbohydrate, proteins and fat and minerals (copper, iron, potassium, magnesium and zinc) except calcium and phosphorus.

2.3 Solar Dryers

Solar radiation incident over India is equal to 4–7 kWh/m^2/day per square meter per day with an annual radiation ranging from 1200–2300 kWh/m^2. It has an average of 250–300 clear sunny days and 2300–3200 hours of sun shine per year (Yadav *et al.*, 2015). Solar dryers are well suitable for harnessing solar energy either by greenhouse effect or with the help of solar absorber materials for heating-up the air for product drying. Solar drying using solar tunnel dryers or solar cabinet dryers are preferred over the conventional sun drying or open yard drying. Mechanical solar drying using natural convection or forced circulation would minimize the disadvantages of traditional open-air drying (Ong, 1999).

Koyuncu (2006) reported an investigation on the performance improvement of greenhouse-type agricultural dryers. The dryer mainly consisted of a 100 × 100 × 100 cm gross dimensions with 1 m^2 net absorbing area with 0.025 mm black coated aluminium sheet as an absorbing material. The trapezoidal frame was covered with 0.15 mm thick polyethylene film. The drying air temperature was recorded 5-9 ^oC more than ambient air. The dryer was experimented for no load and full load (Product: Pepper) test. In addition, an experiment was compared with open sun drying performance. The natural circulation greenhouse dryers for drying agricultural products was found to be 2.5 times more efficient than open air drying due to black coated solar radiation absorber surface and chimney in the dryer.

Kumar and Tiwari (2006) conducted an experiment on natural convection greenhouse drying system for jaggery. Floor area of the greenhouse was 1.20 m × 0.78 m with even span roof covered by UV film. A 0.75 kg and 2.0 kg batches of jaggery cubes were dried from 10 a.m. to 5 p.m. during a day. Thermal performance of the system was observed in which the jaggery temperature was always more than the greenhouse air temperature due to direct solar radiation absorption. The ambient air temperature was lower than greenhouse air temperature.

Sacilik *et al.* (2006) conducted experiment on thin layer drying of organic tomato slices in solar tunnel dryer and reported that the developed dryer could be used for various agricultural products. Tunnel was covered with 150-micron polyethylene semi-transparent film. The temperature and relative humidity inside the tunnel were observed 12.6 ^oC more and 8.7%, respectively, less than ambient conditions. Moisture content was reduced from 93.35% to 11.50% in four days in solar tunnel dryer which was one day less (26.9% less) as compared to open sun drying. Colour quality was also retained more in solar tunnel drying.

Perumal (2007) compared a laboratory developed model of solar cabinet, vacuum assisted solar dryer and open sun drying for drying of tomato slices. The temperatures inside the solar cabinet and vacuum chamber were observed to be 63 and 48 ^{o}C whereas maximum ambient temperature was only 30 ^{o}C. The tomato slices were dried from 94.0 to 11.5% on wet basis moisture content. The 4-, 6-and 8-mm thick tomato slices were dried in 300, 420 and 570 minutes, respectively, in solar cabinet dryer, 360, 480 and 600 minutes, respectively, in vacuum assisted solar dryer and 435, 615 and 735 minutes, respectively, under open sun drying method.

Bahloul *et al.* (2009) studied the convective solar drying of olive leaves (*Olea europaea L.*). The study reported the effect of solar drying conditions on drying time and quality of the product. The leaves were dried at 40, 50 and 60 ^{o}C of temperature and 1.62 m^3/min and 3.3 m^3/min of air flow rate. The drying time was depended on drying temperature. Colour values indicated the reduction in the greenness of the leaves. Total phenolic content was decreased significantly with increase in drying time.

Akpinar (2010) investigated thin-layer drying characteristics of mint leaves in solar cabinet drying with forced convection and open sun drying with natural convection. An indirect forced convection solar dryer had solar collector and drying cabinet. The ambient air temperature was 30 to 46.4 ^{o}C, whereas temperature of drying air at inlet and outlet of drying chamber was 51.5 to 66.3 ^{o}C and 44.1 to 32.4 ^{o}C, respectively. Moisture content of mint leaves was reduced from 6.14 (g water/ g dry matter) to 0.05 (g water/ g dry matter) in solar cabinet drying. It was reduced to 0.09 (g water/ g dry matter) in open sun drying. Drying time was almost half for solar cabinet drying (12,600 seconds) as compared to open sun drying (23,4000 seconds). Energy utilization ratio (EUR) of cabinet drying varied in the ranges between 7.83% and 46.29%.

Janjai (2012) studied the inside environment of greenhouse type small scale solar dryer covered with polycarbonate sheet. The drying air temperature in the dryer varied from 35 ^{o}C to 65 ^{o}C. Relative humidity of inside atmosphere was recorded lower as compared to ambient one. In addition, the drying time was observed 2-3 days shorter for osmotically dried tomatoes as compared to sun drying.

Anil *et al.* (2013) performed an experimental analysis of greenhouse dryer in no-load conditions. An even span greenhouse with effective floor area of 1.50× 1.01 m^2 was constructed with the help of PVC pipe and roof was covered with 3 mm polycarbonate sheet. The maximum temperature and humidity were recorded 40.6 ^oC and 62.6% for natural convection of air, respectively.

Sanusi *et al.* (2013) investigated performance of different solar dryers for preservation of agricultural produces for future use. The evaporated mass of moisture content for tomatoes was observed for open sun drying and passive dryers: direct and indirect type. The results showed that the direct type passive solar dryer performed higher than the indirect one and open drying. The temperature difference showed higher in direct dryer followed by indirect then open drying. Direct dryer showed highest daily average moisture evaporation.

Arekornchee *et al.* (2014) studied drying of rubber sheet in solar greenhouse dryer model. The dryer dimensions were 1 m × 1 m × 1 m with polycarbonate cover. Peak temperature inside the dryer was increased to 60 ^oC at noon. The temperature inside the dryer was 10 ^oC higher than the average ambient temperature. About 30% initial moisture content of rubber sheets was reduced to 2.5% within 5 days.

Kamble and dombale (2015) conducted experiment on preparation of ready-to-use powder from tomato using solar cabinet dryer integrated with heat storage system. The dryer was developed and evaluated for its performance for drying of tomato slices. Ten kg slices per batch were dried in dryer and compared with open sun drying method. The maximum temperature was observed to be 52.63 °C. Drying time was observed to be 12 h 30 minutes to reduce final moisture content from 94% to 8.97%. Under open sun drying, 15 hours was observed for drying of tomato slices. Heat is supplied for 3 more hours after sunset for completion of drying in single day drying.

Prakash *et al.* (2016) analysed modified greenhouse dryer operating under active and passive mode of drying. Dimensions of the dryer was 1.5 m in length, 1.0 m in width and 0.5 m in side height with even span roof top. The frame was covered with polycarbonate sheet except north wall. Tomato, potato and capsicum were dried under open sun drying, active drying and passive drying for comparison. For medium moisture crops, active and passive modes of drying were similar. Crops dried inside the greenhouse drier were found more nutritious than open sun drying. Cost of the active dryer and passive dried were Rs. 12,845 and Rs. 8,995, respectively, with polycarbonate sheet cost of Rs. 5,683 for 3.25 m^2. The payback period for active and passive dryers was 1.89 years and 1.11 years, respectively.

Arjoo *et al.* (2017) evaluated performance of solar tunnel dryer made up of polyethylene for drying of garlic. About 400 kg of garlic was dried from 66% moisture content to 9% in 9 days inside the tunnel dryer. The range of 26 to 64 ^{o}C temperature was recorded inside the solar tunnel dryer. Temperature variation of 8-30 ^{o}C was recorded between ambient and inside temperature of tunnel during drying process. The average thermal efficiency during drying was estimated to be 13.45%.

Sengar *et al.* (2018) evaluated solar tunnel dryer glazed with UV protected polyethylene film. Under the no-load and load conditions of tunnel, maximum temperatures were recorded to be 45.6 ^{o}C and 46.6 ^{o}C at 1 p.m. noon, respectively. The ambient temperature of atmosphere at 1 p.m. was 28.3 ^{o}C with solar radiation intensity of 496 W/m^2. During drying, moisture content of Heena, Neem, Sargava and Tulsi leaves were 62.8%, 74.67%, 69.6% and 71.30%, respectively, which were reduced to below 10% within 8 h, 6 h, 8 h and 8 h, respectively.

Subin *et al.* (2018) analysed two different materials (polyethylene and polycarbonate) used for greenhouse roof covering structure using CFD simulation. Polycarbonate cover of green house with 2 mm thickness had maximum surface temperature of 55.55 ^{o}C and the polyethylene cover with same thickness had 53.16 ^{o}C. Polycarbonate cover with 4 mm thickness absorbed more solar radiation as compared to 2 mm thickness.

Vaghela *et al.* (2018) compared solar tunnel drying and open sun drying for *Moringa oleifera* leaves. Results showed that maximum temperature inside the solar tunnel dryer was 46.5 ^{o}C at 1 p.m. and at the same time ambient temperature was 32.2 ^{o}C for open sun drying. Time required to reduce moisture content from 71.6% to 7.9% was 4 hours for tunnel dryer while 7 hours for open sun drying.

2.4 Biomass Energy Dryers

Biomass can be a promising way to get renewable energy for drying agricultural commodities. It has been estimated that 686 MT of crop residues generated in India every year, out of which 234 MT (34%) is estimated as surplus for bio-energy production (Hiloidhari *et al.*, 2014). Ravindranath *et al.* (2005) reported that in India, production of a gross crop residue biomass was 626.5 MT during the year 1996-97 that increased up to 840 MT by 2010. According to Purohit (2009); annually 74 MT of crop residue could be utilized for energy generation. Singh and Gu (2009) mentioned a gross potential of 1,055 MT per year including residues from spice and plantation crops such as rubber and coffee. Considering rice straw alone, Gadde *et al.* (2009) reported that more than 22 MT straw is available as surplus annually in India.

The present climatological and economic situation of the country demands eco-friendly biomass-based dryers with cheap energy source for the drying applications. Biomass dryers are well suitable to tackle on-farm drying problems. The hot gases from the biomass would be utilized to heat the air inside the drying chamber with the help of a pipe heat exchanger and an automatic temperature control mechanism that allows the temperature of air inside the drying cabinet to be maintained in the range 55-60 °C (Kumar and Bhattacharya, 2005).

Thanaraj *et al.* (2004) developed a small-scale dryer with biomass furnace for the drying of copra. The furnace was fired with 3 kg, 5 kg and 10 kg of paddy husk per hour and the temperature inside the drying chamber were observed to be 43, 53 and 62 ^{o}C, respectively, with furnace efficiency of 43%, 48% and 70%, respectively.

Bello *et al.* (2010) studied the comparison of charcoal, rice husk and sawdust used for heating oven. About 0.01 m^3 of each fuel were fired in the heating chamber until all the material completely burnt out. Air was supplied by natural convection through ducts.

The drying chamber was lagged (insulated) by a 25.4 mm air space between inner wall and the outer casing to prevent heat loss. The results indicated that the highest combustion properties would be exhibited for saw dust (2.68 kJ/h), followed by charcoal (2.54 kJ/h) and rice husk (1.96 kJ/h). The overall furnace efficiency of the oven was 75% and drying chamber efficiency was 62%.

Yunus *et al.* (2011) designed a biomass burner cum flue gas to air heat exchanger to dry 2.5 kg of palm fiber. The design was divided into two parts; lower part was used for wood burning and upper one acts as heat exchanger. The upper part was consisted of two zones i.e. inner zone carried the hot flue gas, while outer zone allowed fresh air movement. The flue gas temperature was recorded as 350 ºC. The heat exchanger with 8 holes of 25.4 mm diameter drilled on the outer surface to permit ambient air to flow through outer zone.

Yassen *et al.* (2013) carried out the performance investigation of a thermal back-up system for hybrid drying to overcome a major setback in the solar drying in which solar energy could not be used during cloudy and rainy days as well as during night. Coal was used as a biomass energy source at the feeding rate 0.426 and 0.271 kg/h. The maximum temperature of the supplied hot air was 60 ºC at the feeding rate of 0.426 kg/h and 40 ºC at 0.271 kg/h.

Hiloidhari *et al.* (2014) considered 39 crop residues generated by 26 crops (Cereals, oilseeds, pulses, sugarcane, horticultural and others). The gross residues available in India were stated 686 MT annually, out of which 234 MT (34% of gross) available as a surplus. About 89% of residues were contributed by the states Andhra Pradesh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Tamil Nadu and Uttar. The contribution was classified as 545 MT was contributed by cereals, oilseed, pulses and sugarcane crops together; 61 MT by horticultural crops (coconut, banana and areca nut) and 80 MT by others (cotton and jute). Cereals contributed the highest amount of residue (368 MT) followed by sugarcane (111 MT).

Thanompongchart *et al.* (2017) compared LPG dryer with biomass energy dryer for drying of glutinous rice crackers to reduce the moisture content from 85-90% (d.b.) to 10% (d.b.). The heating value of biomass used was 12 MJ/kg and the capacity of dryer was 250 kg/batch. The temperature inside the dryer was recorded up to maximum 70 ^{o}C within 6-7 h at 10kg/h of biomass feeding rate. After reaching the maximum temperature, feeding of biomass was stopped and fan was still operated to circulate air. The drying rate was achieved in the range of 6.5 to 8.7 kg/h for different shaped rice crackers with drying time of 15 to 20 h. Overall thermal efficiency was improved from 12% for LPG dryer to 35% using biomass energy.

2.5 Solar-cum-Biomass Energy Hybrid Dryers (Hybrid Dryers)

Owing to intermittent solar radiation throughout the day, continuous drying of agricultural products can be accomplished through a combination of solar and non-solar heating sources in a mixed mode system. Auxiliary heating sources are used to provide uninterrupted supplies of thermal energy for the continuous operation of dryers, during periods of limited solar radiation like night time and cloudy. Biomass is the most widely used as an auxiliary heating source due to its availability and cost effectiveness in rural areas of developing countries (Okoroigwe *et al.*, 2013).

Bena and Fuller (2002) studied the drying characteristics of direct-type solar dryer with natural convection, which was combined with a simple biomass burner for drying fruits and vegetables at small-scale processing units in non-electrified areas. The capacity of the dryer was 20-22 kg of single layer 0.01 m thick fresh pineapple slices. It took 3.5 days to dry the slices from 559% d.b moisture content to 11% d.b. About 47% amount of moisture was removed by solar energy only. The overall thermal efficiency was found to be approximately 9%. However, the drying efficiency of the solar component alone was found to be 22%.

Madhlopa and Ngwalo (2007) studied an indirect type natural convection solar dryer which was integrated with thermal collection system. The major components were biomass burner with a rectangular shaped duct and flue gas chimney, collector-storage thermal mass and drying chamber. The dryer was fabricated using simple materials, tools and skills. The drying of pineapple was carried out in batch of 20 kg each for solar, biomass and solar-biomass drying. Results showed that it was possible to dry a batch using solar energy only on clear days. The average final moisture contents of pineapple were 15%, 11% and 13% in the solar, biomass and solar-biomass, respectively.

Leon and Kumar (2008) evaluated the performance of solar-assisted biomass drying system. Rock bed was charged during day time by burning of biomass. Eucalyptus wood chips (14.8 kg) were used to heat the rock bed. That rock bed provided required heat during night. The hybrid dryer was designed for 24-hour a day drying operation. Temperature of drying air was achieved 60 ºC for 32.5 hours to dry chilli from 76.7% moisture to 8.4% moisture. The system reduced drying time of chilli by 26% approximately as compared to open sun drying. The colour of chilli dried under hybrid system was also brighter than solar cabinet dryer. Higher quality in texture, shrinkage and aroma of chilli was observed in hybrid drying.

Geramitchioski *et al.* (2011) developed a mobile combine solar-biomass dryer for drying of vegetables and fruits with capacity suitable for small farm and cooperatives. The stove used for biomass gasification consumed 2 kg of wood per hour and 4 kg of briquette per hour to provide 60 ºC drying air temperature. The solar energy harnessing material was polyethylene film with dryer capacity of 50 kg sliced fruits or vegetables. The apples were dried at 60-70 ºC for an average drying time of 8 sunshine hours to attain a final moisture content of 20%.

Gunasekaran *et al.* (2012) studied on modelling and analytical experiment of hybrid solar dryer integrated with biomass dryer for drying *Coleus Forskohlii* stems. The results showed that the integrated hybrid model produced best optimum results. Hybrid model produced the stems with moisture content of 12.3%, whereas solar dryer resulted 33% and biomass resulted 19.6% of final moisture content.

Al-Kayiem and Yunus (2013) conducted an experiment on hybrid solar/biomass thermal backup dryer. The Empty Fruit Bench (EFB) was dried under open sun, mixed solar direct and indirect, thermal backup and hybrid modes of drying. The thermal backup unit was installed with gas-to-gas heat exchanger. Heated air was coming out from exchanger at 50 to 65 ^oC. Solar drying would require 52 to 80 hours while open sun drying needed 100 hours to dry the product. Thermal backup reduced the drying time to 48- 56 hours and hybrid mode required only 24-32 hours. The hybrid mode of drying enhanced the drying performance.

Andrew *et al.* (2013) developed an indirect solar dryer with biomass backup burner for drying pepper berries. A prototype was designed and developed for the use of small-scale rural farmers. The drying time in the traditional drying was observed to be 5-7 days for whole drying process whereas developed solar dryer had taken shorter drying time of 11 hours of day time solar radiation and 6 hours of night time with biomass burning. The highest and lowest temperatures (due to rain) were recorded at 34.7 ^oC and 26.8 ^oC, respectively. The average initial and final moisture content of berries was found to be 76.6% w.b. and 12% w.b., respectively.

Okoroigwe *et al.* (2013) studied an efficiency of agricultural dryers and showed that efficiency could be increased through the use of a combination of solar and biomass heating sources, compared to conventional dryers with only solar or only biomass heating sources. Yam chips were dried over a test period of 4 days under different drying. Maximum 53 ^oC tray temperature was obtained in combination with solar and biomass heating as compared to ambient temperature (24 to 30 ^oC). The drying rate of 0.0142 kg/h was achieved with the combined solar and biomass dryer. The drying rate for solar and biomass drying was observed to be 0.00732 kg/h and 0.0032 kg/h, respectively.

Dhanushkodi *et al.* (2015) conducted the study on life cycle cost of solar-biomass hybrid dryer systems for cashew drying in India. Drying system of 40 kg were proposed for application in small scale cashew nut processing industries. Payback time was recorded to be 1.58, 1.32 and 1.99 years for solar, biomass and hybrid drying system, respectively. The cost-benefit estimate was 5.23 for solar, 4.15 for biomass and 3.32 for the hybrid system. The cost of drying (Rs. 0.8/kg) and initial investment (Rs. 61,732) for cashew kernel was lowest for solar drying.

Shyam *et al.* (2015) conducted an economic analysis for drying one batch each of 106 kg green chillies and 102 kg green spinach leaves in solar alone, solar–biomass, and hybrid modes of operation. Cost of the fuel wood and the electricity used were taken as Rs.5/kg and Rs.8/unit, respectively. Four unskilled workers (wages at the rate of Rs.200/day) were engaged for pre-treatment of the produce and carrying out the drying operation. Operating cost of the biomass combustor per hour for drying green spinach leaves and green chillies have been worked out to be Rs. 150/hour and Rs. 137/hour, respectively. The cost computations clearly revealed that solar–biomass and hybrid modes of drying saved Rs. 270 - Rs. 665 per batch as compared to solar alone mode of operation, primarily because of major reduction in cost of the manpower. The batch drying operation was completed in one day in solar–biomass and hybrid modes as against two days in solar alone mode.

Sonthikun *et al.* (2016) designed and constructed the solar-biomass hybrid dryer for natural rubber sheet drying. The dryer consisted of solar collector cum drying chamber, heat exchanger and biomass furnace. The indirect solar heating of rubber sheet was attempted to reduce consumption of biomass. Computational fluid dynamics (CFD) technique was used to simulate the temperature and air flow distributions. The results for temperature were found experimentally good. Air flow CFD simulation was done to ensure the utility of air circulating fans. The hybrid dryer was tested for drying of 100 number of natural rubber sheets for reduction in moisture content from 34.26% to 0.34 % d.b. in only 48 h. A notable reduction in drying time and consumption of biomass were observed. The colour and texture of the natural rubber sheet were noticed better than the traditional smoke rubber drying.

Yahya (2016) designed and evaluated a solar assisted heat pump dryer integrated with biomass furnace for drying red chillies. Average drying chamber temperature and relative humidity were 70.5 ^{o}C and 10.1% for air flow rate of 0.124 kg/s. Time required for 22 kg of product were observed to be 11 h to reduce the moisture content from 4.26% (d.b.) to moisture content of 0.08% (d.b.). Open sun drying time was observed to be 62 hours. The designed dryer yielded 82% saving in drying time as compared to open sun drying. The drying rate, the specific moisture extraction rate, and thermal efficiency of the dryer were estimated to be about 1.57 kg/h, 0.14 kg/kWh, and 9.03%, respectively.

Yuwana and Sidebang (2016) tested performance of hybrid solar-biomass dryer for fish drying. The drying operation was carried out from 9 a.m. to 4 p.m. with solar drying followed by biomass drying up to 2 a.m. of the next day. The drying time was compared with sun, only solar and only biomass drying. Drying time was found to be 24.4 hours, 14.4 hours, 15.4 hours and 24.2 hours in solar, biomass, solar-biomass and sun drying, respectively.

Padmapani *et al.* (2019) conducted experiment on hybrid solar dryer for drying of high-value flowers. The hourly ambient temperature and dryer temperature difference was recorded and found that maximum difference was 26 ^{o}C. The flowers were dried using the solar dryer provided superior quality products and better overall acceptability compared to open sun drying under embedded condition. The time of drying in a solar dryer was found to reduce by 65% and 70% for rose and marigold flowers, respectively than in open sun.

The above reviews were evidence of this study that development of the solar-cum-biomass hybrid dryer for simarouba leaves would be an effective attempt with good design and performance. The design was lacking in the list of attempts. Further, different drying methods for simarouba leaves were not tested. Hence, the study on development of hybrid dryer was considered appropriate.

III MATERIALS AND METHODS

This chapter deals with the materials and methods used during the development of solar-cum-biomass energy hybrid dryer and the drying studies on simarouba leaves. The information on location of drying experiments, materials used in the study, properties of simarouba leaves, components of solar-cum-biomass energy hybrid dryer, design considerations and fabrication of the dryer and different methods used for drying simarouba leaves are discussed in detail. This chapter also includes instrumentation used in the present investigation and the phytochemical analysis of dried simarouba leaves. The methodology of the present study was planned and carried out after detailed review of published literatures as presented in the Chapter II.

3.1 Location of Experiment

The present investigation on "Development of Solar-Cum-Biomass Energy Hybrid Dryer for Simarouba Leaves" was carried out at ICAR- All India Co-ordinated Research Project on Post Harvest Engineering and Technology, University of Agricultural Sciences - Bangalore, Gandhi Krishi Vigyan Kendra (GKVK), Bengaluru, Karnataka, India and College of Agricultural Engineering, University of Agricultural Sciences - Bangalore, GKVK, Bengaluru, Karnataka, India during the year 2019-2020. The latitude and longitude of the location of investigation is 13.0801° North - 77.5785° East. The study area lies at an altitude of 924 meters above the mean sea level.

3.2 Materials

Well matured, diseases free, fresh and healthy leaves of simarouba (*Simarouba glauca*, Plate 3.1) were harvested from the trees of GKVK campus, Bengaluru. After harvesting, leaves were washed thoroughly in tap water and drained well for further studies. The fabrication materials like glazing materials, metal sheets, angle bars, fan (wind turbine), wheels and other required materials for development of solar-cum-biomass energy hybrid dryer were purchased from the local markets of Bengaluru. The chemicals used in this study were of analytical grade unless stated.

3.3 Properties of Simarouba Leaves

The physical properties of simarouba leaves like size, surface area, bulk density, true density, colour and 1000 leaves weight of simarouba leaves were measured. The moisture content, dry matter and phytochemical properties (total phenols and total flavonoids) of leaves were also determined using standard methods.

3.3.1 Size and surface area

Size of the 10 randomly selected matured simarouba leaves were measured in terms of different dimensions like length (cm), width (cm) and thickness (cm) with the help of Vernier calliper (Make: Mitutoyo; Range: 0-150 mm; Least count: 0.01 mm) and Micrometre (Make: Mitutoyo; Range: 0-25 mm; Least count: 0.01 mm).

Surface area (cm^2) was measured by tracing a leaf area on Cartesian graph paper. Numbers of square were counted and surface area was calculated using the following equation;

$$\text{Surface area} = (1 \times \text{a}) + (0.75 \times \text{b}) + (0.50 \times \text{c}) + (0.1 \times \text{d}) \qquad \text{... Eq (1)}$$

Where,

a = No. of squares fully traced

b = No. of squares which are traced 75%

c = No. of squares which are traced 50%

d = No. of squares which are traced 10%

3.3.2 Bulk density and true density

Bulk density (kg/m^3) was calculated by the ratio of weight of leaves (kg) to volume of container (m^3) in which leaves were filled. True density of leaves was measured with the help of water displacement method by measuring volume of water displaced by sample in a graduated measuring cylinder.

3.3.3 Colour measurement and 1000 leaves weight

Spectrophotometer (Make: Konica Minolta Instrument, Osaka, Japan, Model - CM5) was used for the measurement of tristimulus colour values of fresh leaves of simarouba (Plate 3.2). Spectrophotometer was calibrated with black and white standard plates prior to colour analysis. The colour of the sample was measured in L* a* b* coordinate system; where L* indicate lightness of the sample; a* value indicate greenness (-) or redness (+) of the sample; and b* value indicate blueness (-) or yellowness (+) of the sample (Darshan, 2015).

1000 leaves weight of simarouba leaves was measured by electronic weighing balance (Plate 3.3; Make: Adam Equipment Co. Ltd.; Capacity: 15 kg, Least count: 0.0001 kg).

3.3.4 Moisture content and dry matter

Moisture content of fresh leaves of simarouba was measured with hot air oven method using standard reference of AOAC (2005) with three replications. Three grams of sample were weighed in a moisture cups and placed in a hot air oven at 105 ± 1 ^{o}C for about 24 hours to dry up to bone dry level. After cooling, the moisture content was measured by measuring weight loss of sample in a moisture box by desiccation in oven until constant weight and expressed in both percentage wet basis (% w.b.) and percentage dry basis (% d.b.) as given in the equations (2) and (3), respectively. Dry matter was estimated by difference of moisture and total weight as given by Darshan (2015).

$$\text{Moisture content } (\% \text{ w.b.}) = \frac{[W_1 - W_2]}{W_1} \times 100 \qquad \text{... Eq (2)}$$

$$\text{Moisture content } (\% \text{ d.b.}) = \frac{[W_1 - W_2]}{W_2} \times 100 \qquad \text{... Eq (3)}$$

Where,

W_1 = Initial weight of leaves (kg)

W_2 = Final weight of leaves (kg)

3.3.5 Total phenols and total flavonoids

Total phenols (mg Gallic Acid Equivalents /100 g) of fresh simarouba leaves were measured using spectrophotometry method as described by Singleton and Rossi (1965). For total phenol estimation, 1 g of fresh leaves was crushed in pestal and mortar and leaf extract was obtained using 80% methanol (20 ml). The extraction was repeated twice and the volume was made up to 50 ml from the pooled extracts. One ml of extract was taken and diluted with 80% methanol for required volume. About 0.2 ml of Folin Ciocalteu Reagent (FCR) was added to 0.5 ml of diluted extract followed by addition of 3.3 ml of distilled water and the solution was thoroughly mixed. After 2 minutes, 1 ml of sodium carbonate solution was added, thoroughly mixed in test tubes and incubated at room temperature for 30 minutes. The intensity of blue colour was measured in a spectrophotometer (Make: Systronics, Model: UV-VIS 118) at 700 nm. Standard curve for phenols was prepared using gallic acid as a standard and the total phenols were calculated by the equation (4).

$$\text{Total phenols (mg Gallic Acid Equivalents/100g)} = \frac{\text{OD}_{700} \times \text{Std. value } (\mu\text{g/OD}) \times \text{Total extract Vol.} \times 100 \times \text{Dilution factor}}{\text{Assay volume} \times \text{Weight of sample (g)} \times 1000}$$

... Eq (4)

Total flavonoids **(**mg Quercetin equivalents /100 g) of fresh simarouba leaves were estimated using quercetin as a standard and absorbance was measured using spectrophotometer (Make: Systronics, Model: UV-VIS 118) as described by Chun *et al.*, (2003). Methanolic extracts (1 ml) obtained during estimation of total phenols were taken and diluted with 80% methanol for required volume. Diluted extract was filled in test tube and 0.3 ml of 5% $NaNO_2$ was added twice at an interval of 2 minutes. Similarly, 3.4 ml of 4 N NaOH was added after 2 minutes and the mixture was incubated at room temperature for 10 minutes. The brick red colour was measured at 510 nm in spectrophotometer and the total flavonoids were calculated using the equation (5).

Plate 3.1: Leaves of Simarouba (*Simarouba glauca*)

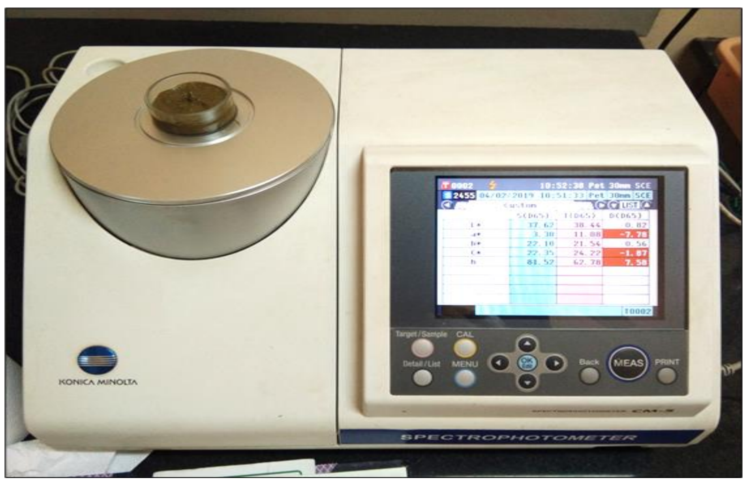


Plate 3.2: Spectrophotometer

Plate 3.3: Digital electronic weighing balance

$$\text{Total flavonoid content (mg Quercetin equivalents/100g)} = \frac{\text{OD}_{510} \times \text{Std. value (mg/OD)} \times \text{Total extract Vol.} \times 100 \times \text{Dilution factor}}{\text{Assay volume} \times \text{Weight of sample (g)}}$$

... Eq (5)

3.4 Development of Solar-cum-Biomass Energy Hybrid Dryer

Solar-cum-biomass energy hybrid dryer was designed actually to dry the agricultural products in bulk condition. In this study, however, simarouba leaves were taken as drying material due to its importance as medicinal herb in the field of pharmaceutical industries and also its abundant availability in the study area. The different components of dryer were solar energy collection unit equipped with fan (wind turbine), drying chamber, heat exchanging unit with plenum chamber, biomass fired furnace and main frame with wheels. For the development of model of the hybrid dryer, about 15 kg of fresh simarouba leaves having 64.25% w.b. initial moisture content and 72 kg/m^3 bulk density was considered as drying capacity.

The medicinal herbs are recommended to be dry below 60 ºC to maintain the quality and to preserve the important bio-active compounds (Doymaz *et al.*, 2006). Herbs dried around 10% w.b. moisture content are preferred for extraction of phytochemicals and also to maintain the quality of the product during storage. In this study, therefore, the target was to achieve 55 ºC drying air temperature and about 10% w.b. moisture content of final product. The ambient air temperature was assumed to be 30 ºC for dryer design. The different mathematical equations were considered during the designing of solar-cum-biomass energy hybrid dryer and the assumptions were made wherever necessary. The selection of best glazing material for effective harness of solar energy and the designing of hybrid dryer integrated with solar energy and biomass energy are discussed as given below.

3.4.1 Selection of glazing material

For development of dryer based on solar energy, the selection of glazing material is essential to harness the maximum solar energy. Therefore, six available greenhouse glazing materials *viz.* Acrylic sheet, Ethylene vinyl alcohol (EVOH) film, Fibre glass, Polycarbonate sheet, Polyethylene film and Poly-vinyl Chloride (PVC) sheet were used to observe the temperature profile and relative humidity profile inside solar energy collection units (Plate 3.4). These units were cubic shaped chambers having dimension of 80 cm × 80 cm × 80 cm. It was made with the help of 1-inch mild steel (MS) angle bar frame covered with glazing materials individually. The cubic chambers were exposed to daily sun shine hours in the month of February 2020 from 9:00 a.m. to 4:30 p.m. for 20 days. The temperature profile and relative humidity profile inside the cubic chambers were observed at an interval of 90 minutes with the help of six channel digital temperature indicator (Make: Beltronics, Specifications: Type K thermo-couples, Resolution: 0.1 ^{o}C) and relative humidity recorder (Model: HTC 2), respectively. The data were recorded at different zones like top, middle and bottom of the chamber for 20 days and observed values were averaged for statistical analysis (One-way ANOVA) using Microsoft excel 2010. The experimental design used for selection of glazing materials is given as follows,

3.4.1.1 Parameters for selection of glazing materials

(a) Independent parameters: Types of glazing materials

1. Acrylic (A)
2. Ethylene Vinyl Alcohol (EVOH)
3. Fibreglass (F)
4. Poly Carbonate (PC)
5. Polyethylene (PE)
6. Poly Vinyl Chloride (PVC)

(b) Dependent parameters

1. Average temperature (°C) inside drying chamber
2. Average relative humidity (%) inside drying chamber

3.4.2 Design of drying chamber

Based on the required capacity (15 kg fresh leaves) and the bulk density (72 kg/m^3) of the product, the drying chamber (Plate 3.5a) was designed with the help of following mathematical calculations.

(A) Volume of product for assumed capacity of the dryer, V_d (m^3)

$$V_d = \frac{W_t}{\rho_d} \quad \text{... Eq (6)}$$

Where,

W_t = Weight of the product (kg)

ρ_d = Bulk density of the material (kg/m^3)

$$V_d = \frac{15}{72} = 0.21 \text{ m}^3$$

(B) The diameter of exhaust air channel was fixed to be 0.125 m to suit the fan (wind turbine) which was commercially available in the market. Therefore, the cross-sectional area a_e (m^2) of cylindrical exhaust channel inside the drying chamber was calculated as follows,

$$a_e = \frac{\pi}{4} \times d_e^2 \quad \text{... Eq (7)}$$

Where,

d_e = Diameter of the exhaust channel (m)

$$a_e = \frac{\pi}{4} \times (0.125)^2 = 0.0123 \text{ m}^2$$

(C) Height (h_c) of the drying chamber was fixed to be 0.8 m which was equal to the height (h_e) of the air exhaust channel column inside the drying chamber.

$$h_c = h_e = 0.8 \text{ m}$$

(D) Total volume of the drying chamber V_c (m^3) was calculated as follows,

$$V_c = V_d + V_e = V_d + (a_e \times h_c) \quad \text{... Eq (8)}$$

Where,

V_d = Volume of the product to be dried (m^3)

V_e = Volume of air exhaust channel column (m^3)

a_e = Cross-sectional area of cylindrical exhaust channel (m^2)

h_e = Height of the air exhaust channel column (m)

$$V_c = 0.21 + (0.0123 \times 0.8) = 0.22 \text{ m}^3$$

(E) For bulk drying of the product, cylindrical bins were most suitable, thus drying chamber was designed to be cylindrical in shape. Therefore, the diameter of the drying chamber, d_c (m) was calculated as follows,

$$d_c = \sqrt{\frac{4 \times V_c}{\pi \times h_c}} \quad \text{... Eq (9)}$$

Where,

V_c = Total volume of the drying chamber (m^3)

h_c = Height of the drying chamber (m)

$$d_c = \sqrt{\frac{4 \times 0.21984}{\pi * 0.8}}$$

$$d_c = 0.5915 \text{ m} \approx 0.6 \text{ m}$$

3.4.3 Calculation of total energy requirement for drying

The total energy required for removal of leaf moisture from 65% to 10% during drying was calculated as follows,

(A) Total weight of water in the product, W_{tw} (kg)

$$W_{tw} = W_t \times \frac{M_i}{100} \quad \text{... Eq (10)}$$

Where,

W_t = Weight of wet product (kg)

M_i = Initial moisture content of the product (% w.b.)

$$W_{tw} = 15 \times \frac{65}{100} = 9.75 \text{ kg}$$

(B) Bone dry weight of the product, W_b (kg)

$$W_b = W_t - W_{tw} \qquad \text{... Eq (11)}$$

Where,

W_t = Weight of the wet product (kg)

M_{tw} = Total weight of water in the product (kg)

$$W_b = 15 - 9.75 = 5.25 \text{ kg}$$

(C) Weight of water to be removed during drying, W_w (kg)

$$W_w = \frac{M_i - M_f}{100 - M_f} \times W_t \qquad \text{... Eq (12)}$$

Where,

M_i = Initial moisture content of the product (% w.b.)

M_f = Final moisture content of the product (% w.b.)

W_t = Weight of wet product (kg)

$$W_w = \frac{65 - 10}{100 - 10} \times 15 = 9.17 \text{ kg}$$

(D) Total energy required to remove the moisture, Q_n (kJ) as given by Kishore *et al.* (2014) was calculated using the equation (13). The specific heat of simarouba leaves was not available, thus, specific heat of mango leaves was considered for calculations (Jayalakshmy and Philip, 2010).

$$Q_n = W_t \times C_p \times (T_d - T_a) + W_w \times \lambda \qquad \text{... Eq (13)}$$

Where,

W_t = Mass of the wet product (kg)

C_p = Specific heat of product (kJ/kg.^{o}C)

T_d = Drying temperature (^{o}C)

T_a = Ambient temperature (^{o}C)

W_w = Weight of the water removed (kg)

λ = Latent heat of vaporization of water (kJ/kg)

$$Q_n = 15 \times 1.545 \times (55 - 30) + 9.17 \times 2260$$

$$Q_n = 21303.575 \text{ kJ}$$

3.4.4 Design of heat exchanging unit with plenum chamber

Heat exchanging unit with plenum chamber was designed to suit the drying chamber. Rectangular shaped heat exchanging unit contained heat exchanging duct (Plate 3.5b) inside the rectangular shell (Plate 3.5c) was attached with the inverted pyramid shaped plenum chamber (Plate 3.5d). The size of the heat exchanging unit was based on duct size. The CAD design of the duct and the shell of biomass heat exchanging unit is presented in Plate 3.6a and Plate 3.6b, respectively. The biomass fired furnace available in the workshop of ICAR-AICRP on PHET, Bangalore was used to burn the briquettes as biomass and produce the flue gases as energy source. The rate of drying air required in drying chamber for moisture removal, air draft at exhaust channel and cross-sectional area of duct size was calculated using the following equations as described by Anoosha (2018).

(A) Rate of air needed to absorb M_w kg of water, Q_a (m^3/h)

$$Q_a = \frac{Q_n}{\rho_a \times C_{pa} \times (T_d - T_a) \times t} \quad \text{... Eq (14)}$$

Where,

ρ_a = Density of the ambient air (kg/m^3)

C_{pa} = Specific heat of ambient air (kJ/kg.^{o}C)

T = time for drying operation (h) (Assumed: 8 hours)

$$Q_a = \frac{21303.575}{1.252 \times 1.005 \times (55 - 30) \times 8}$$

$$Q_a = 84.65 \ {m^3}/{h}$$

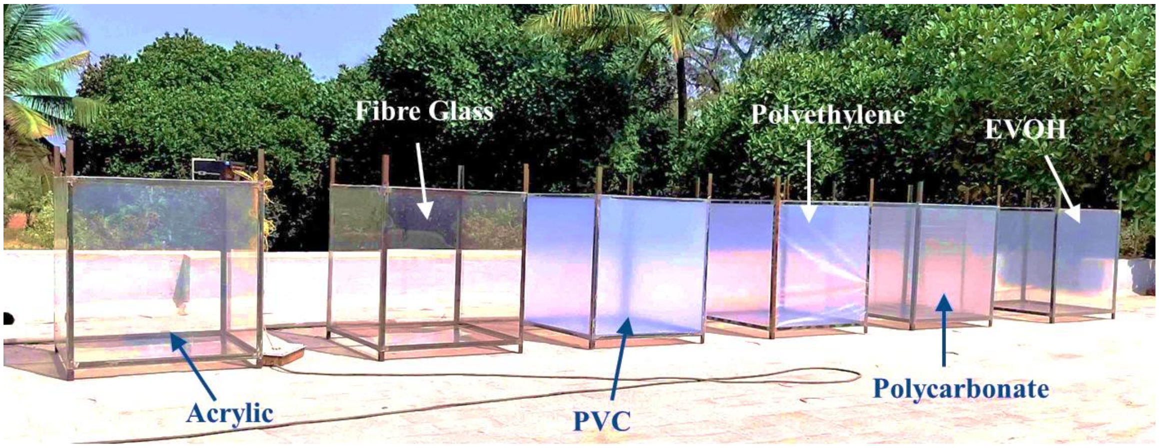


Plate 3.4: Setup for temperature profile study inside different glazing

(a)

(b)

(c)

(d)

Plate 3.5: (a) Drying chamber (b) Duct of heat exchanger (c) Shell of heat exchanger (d) Heat exchanging unit with plenum chamber

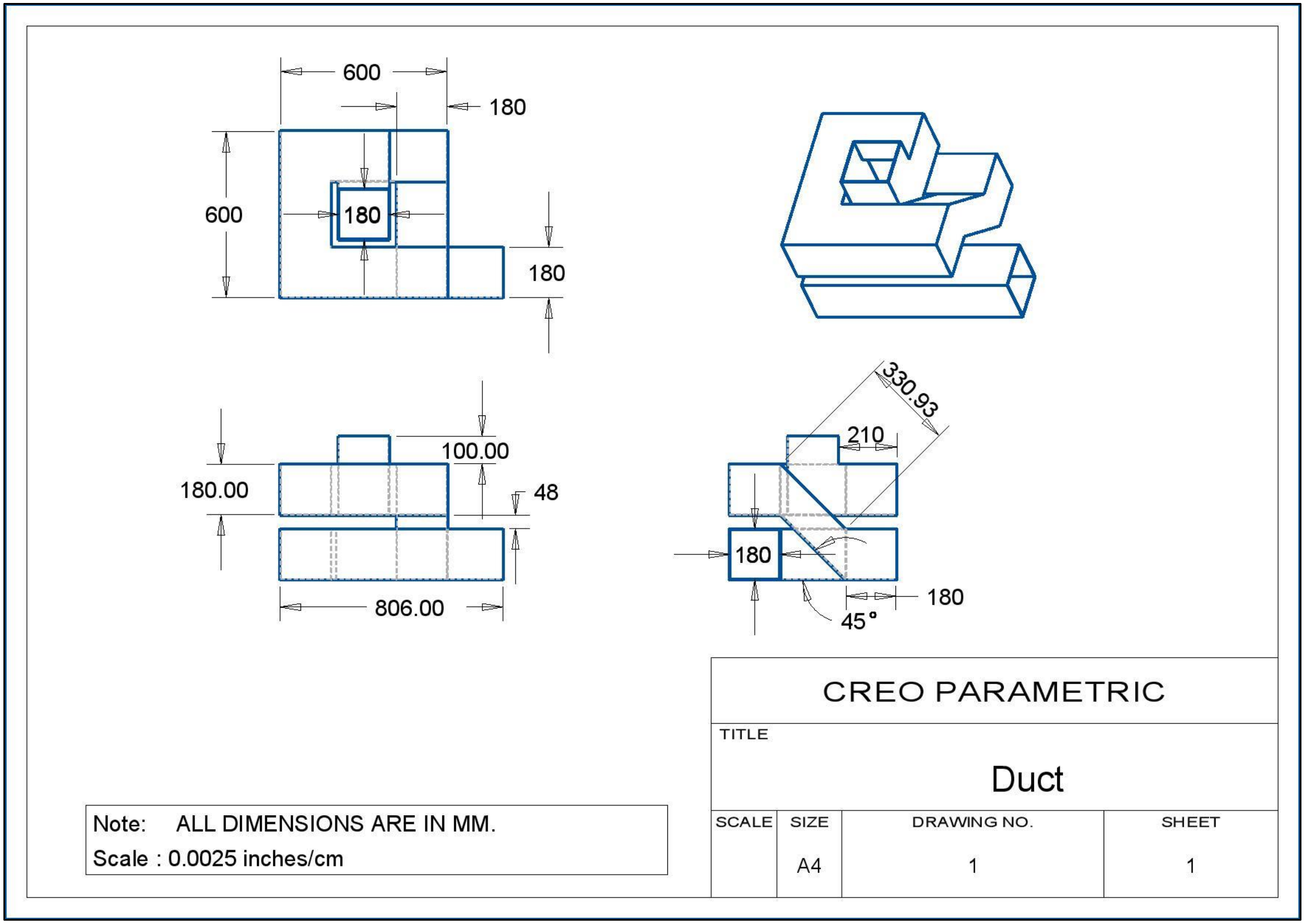


Plate 3.6: (a) CAD design: Duct of biomass heat energy exchange unit

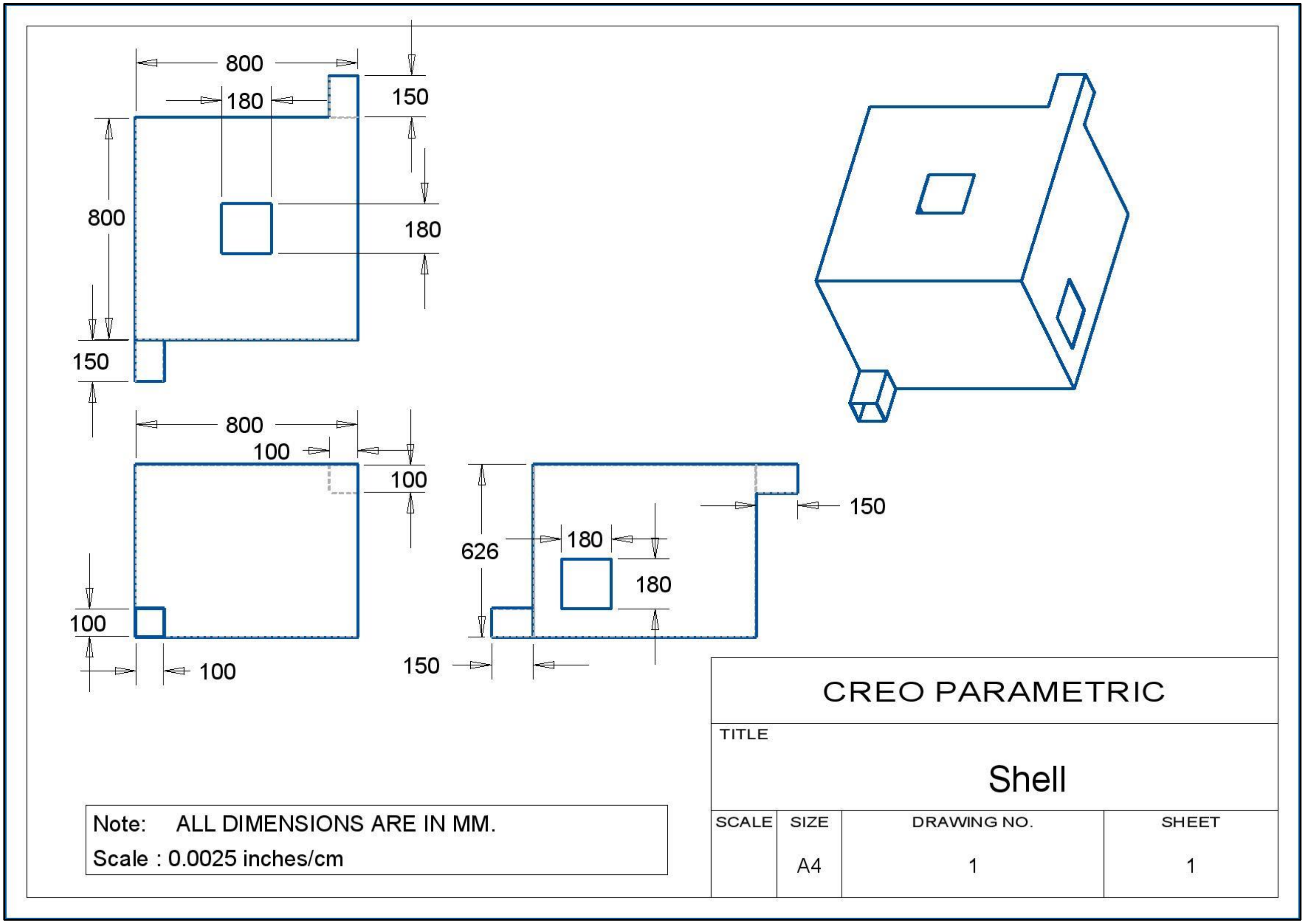


Plate 3.6: (b) CAD design: Shell of biomass heat energy exchange unit

(B) Air drafts into environment through exhaust channel, q_a (m^3/h)

$$q_a = a_e \times v_a \qquad \text{... Eq (15)}$$

Where,

a_e = Cross-sectional area of cylindrical exhaust (m^2)

v_a = Velocity of air (m/h) (Assumed: 7 kilometre per hour)

$$q_a = 0.0123 \times 7 \times 1000 = 86.1 \ \mathrm{m^3}/\mathrm{h}$$

Additionally, 2.5 times excess air quantity was considered due to air pockets inside the drying system during lateral flow through bulk material.

$$'q_a = q_a \times 2.5 = 86.1 \times 2.5 = 215.25 \ \mathrm{m^3}/\mathrm{h} \qquad \text{... Eq (16)}$$

(C) Cross-section area of duct inlet, a_d (m^2)

$$a_d = \frac{q'_a}{v_a} \qquad \text{... Eq (17)}$$

Where,

q'_a = quantity of air needed to supply (m^3/h)

v_a = Velocity of air (m/h)

$$a_d = \frac{215.25}{7 \times 1000} = 0.031 \ \mathrm{m^2}$$

$$= 0.1754 \ \mathrm{m} \times 0.1754 \ \mathrm{m}$$

$$\approx 0.18 \ \mathrm{m} \times 0.18 \ \mathrm{m}$$

Solar-cum-biomass energy hybrid dryer was fabricated in the workshop of ICAR - AICRP on Post Harvest Engineering and Technology, UAS, Bangalore considering above design criteria. All fabrication materials were procured from the local markets of Bengaluru.

3.5 Studies on Drying Kinetics of Simarouba Leaves

Drying kinetics of simarouba leaves dried under solar-cum-biomass energy hybrid drying technique were carried out and compared with other drying methods to evaluate the effect on drying time and the quality of the final product. Six different drying methods like shade drying, sun drying, tray drying, solar drying, biomass drying and solar-cum-biomass energy hybrid drying were used to dry the simarouba leaves. Fresh and matured leaves after washing and draining were used for drying studies and the experiments were replicated thrice. Drying data such as initial, intermediate and final moisture content of the drying material, temperature and relative humidity of drying air, exhaust air and ambient air were measured at regular interval with drying time. Using these data, drying rate (DR) and moisture ratio (MR) were calculated and drying characteristics curves were plotted. The effect of drying methods on drying time and quality of the dried products was studied. The determination of the quality of the dried product was based on analysis of colour and phytochemical properties (total phenols and total flavonoids) of the leaves as described in section 3.3.3 and 3.3.5, respectively. The difference in L*, a*, b* values of fresh and dried leaves were used to calculate colour change or total colour difference (ΔE*) using the following Hunter–Scotield equation as described by Spada *et al*. (2012):

$$\Delta E* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}} \quad \text{... Eq (18)}$$

Both total phenols and total flavonoids were expressed on dry basis. Cost estimation of the developed hybrid dryer was also carried out. The detailed methodology and experimental design for the studies on drying kinetics and the effect of drying methods on drying time and quality of the dried products were discussed as follows,

3.5.1 Different drying methods for simarouba leaves

Six drying methods such as shade drying, sun drying, tray drying, solar drying, biomass drying and solar-cum-biomass energy hybrid drying were used to dry the simarouba leaves. Former three methods were thin layer drying whereas latter three were bulk drying. Shade drying (Plate 3.7a) was carried out under the shade at room temperature to avoid direct exposure of sun-light whereas sun drying of simarouba leaves was carried out in open area as shown in Plate 3.7b. In tray drying method (Plate 3.8a), leaves were dried in electrically operated tray dryer (Make: Macro Scientific Works Pvt. Ltd., Delhi, India; Plate 3.8b) at 55 ± 1 ^{o}C temperature as described by Doymaz *et al.* (2006). In all three thin layer drying methods, 15 rectangular shaped trays (40 cm width and 75 cm length) loaded with 7.5 kg fresh leaves were used. Each tray consisting of about 500 g of fresh samples with bed thickness of 2 cm was used for drying. The drying studies were carried daily until the final product attained the moisture content of ~10% w.b. However, drying data were recorded from 9:00 a.m. to 5:00 p.m. for sun and shade drying at regular interval 2 h. Similarly, drying data was recorded continuously at an interval of 2 h during tray drying.

Drying of simarouba leaves using solar drying, biomass drying and solar-cum-biomass energy hybrid drying technique was bulk drying in which 7.5 kg (half load) of fresh leaves were loaded in the perforated vertical drum (60 cm diameter and 80 cm length) as shown in Plate 3.9 and dried under different condition. In all three methods, drum containing fresh leaves was placed inside the glazed chamber and the drying was carried out individually. In solar drying, the drying chamber was exposed to sun shine from 09:00 a.m. to 07:00 p.m., where as in biomass drying, the drying chamber was placed under shade; heat source for drying was supplied continuously by burning briquette in biomass fired furnace as shown in Plate 3.10. Drying data was recorded continuously in biomass drying, whereas in solar drying, the recording period was only during sun-shine hours (09:00 a.m. to 07:00 p.m.) at a regular interval of 2 h until the final product attained the moisture content of ~10% w.b. In, hybrid drying method, both solar and biomass energy were used to dry the leaves. Here, the drying chamber containing drum loaded with fresh leaves was exposed to solar radiation during sun shine hours (09:00 a.m. to 05:00 p.m.). Meanwhile heat obtained through biomass burning was utilised during non-shiny hours like early morning (07:00 a.m. to 09:00 a.m.), late evening (05:00 p.m. to 03:00 a.m.) and cloudy weather. The recording of drying data in hybrid drying was similar to biomass drying.

In all drying methods, weight loss from the leaves, psychometric data of ambient air and drying air were recorded at regular intervals. Available exhaust air temperatures, initial and final moisture content of the samples were also recorded for calculations. Sampling was carried out for bulk drying in which 500 g fresh leaves packed in the plastic mesh bags/ net bags were placed inside the drying chamber at different zones. These bags were withdrawn periodically for measurement of moisture loss of samples. Drying data obtained during the experiment were subsequently used for calculation of the drying kinetics like drying rate and moisture ratio. Moisture curves were also plotted for all drying methods.

3.5.2. Drying rate and moisture ratio

Drying rate (DR) was determined using Eq (15) based on quantity of water evaporated from the samples and the drying time. The quantity of water evaporated from product during drying was calculated as difference between initial and final weight of the samples (Kamble and Dombale, 2015).

$$DR = \frac{\Delta M}{\Delta t} \qquad \text{... Eq (19)}$$

Where,

DR = Drying rate (kg of water removed/kg of dry matter.h)

ΔM = Quantity of water evaporated from product (kg)

Δt = Time required to dry the product (h)

Moisture ratio (MR), a drying kinetics parameter was calculated by the following mathematical expression described by Kamble and Dombale (2015).

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad \text{... Eq (20)}$$

Where,

M = Moisture content at a given time (% d.b.)

M_e = Equilibrium moisture content (% d.b.)

M_o = Initial moisture content (% d.b.)

(a) **(b)**

Plate 3.7: (a) Shade drying experiment (b) Sun drying experiment

(a) **(b)**

Plate 3.8: (a) Trays loaded with simarouba leaves (b) Tray dryer

Plate 3.9: Drying chamber loaded with simarouba leaves

Plate 3.10: Burning of briquettes in biomass fired furnace

3.5.3 Parameters for studies on effect of drying methods

(a) Independent parameters: Different drying methods

1. Shade drying
2. Sun drying
3. Tray drying
4. Solar drying
5. Biomass Energy drying (Biomass drying)
6. Solar-cum-Biomass Energy Hybrid drying (Hybrid drying)

(b) Dependent parameters

1. Drying time and Drying rate
2. Colour
3. Phytochemical properties of dried simarouba leaves

3.5.4 Performance evaluation and cost estimation of hybrid dryer

The performance evaluation of the developed solar-cum-biomass energy dryer was based on the heat utilization factor. Heat utilization factor (HUF) indicates heat loss during the drying operation. HUF for the dryer was calculated with the help of following equation (Sayyad *et al.*, 2015);

$$\mathrm{HUF} = \frac{T_2 - T_3}{T_2 - T_1} \qquad \text{... Eq (21)}$$

Where,

T_1 = Temperature of ambient air (^{o}C)

T_2 = Temperature of drying air (^{o}C)

T_3 = Temperature of exhaust air (^{o}C)

3.6 Statistics analysis

Temperature and relative humidity data obtained for 20 days for selection of glazing materials were statistically analysed using One-way Analysis of Variance (One-way ANOVA). Effect of different drying methods on drying time, drying rate and quality parameters of dried products (n=3) was also analysed using One-way ANOVA. Statistical analyses were done at 5% level of significance using Microsoft Office Excel 2010. The results are presented with their means and standard deviation.

IV RESULTS AND DISCUSSION

The results of the present study titled "Development of Solar-cum-Biomass Energy Hybrid Dryer for Simarouba Leaves" conducted at GKVK Campus, University of Agricultural Sciences, Bangalore are presented and discussed in this chapter. It includes properties of simarouba leaves, temperature and relative humidity profiles of different glazing materials, design and development details of the solar-cum-biomass energy hybrid dryer, drying kinetics during drying studies of simarouba leaves using different methods and comparison studies of different drying methods.

4.1 Properties of Simarouba Leaves

The properties of fresh simarouba leaves were measured for design and development of hybrid dryer and further analysis. Table 4.1 shows moisture content, dry matter, 1000 leaves weight, bulk density, true density, leaf surface area, total phenols, total flavonoids, size and colour of fresh leaves of simarouba. The leaves contained 64.25 ± 0.76% of moisture (179.79 ± 5.91% d.b.) and 35.75 ± 0.76% of dry matter. The bulk density and true density of fresh leaves were 72.75 ± 4.60 kg/m^3 and 1048.98 ± 34.37 kg/m^3, respectively. The average dimensions (size) of leaves recorded were 8.72 ± 0.74 cm of length, 2.77 ± 0.23 cm of width and 0.045 ± 0.01 cm of thickness. The mean surface area of the well matured fresh leaf was 20.26 ± 2.39 cm^2. Weight of 1000 fresh leaves of simarouba was recorded to be 4.4 ± 0.1 kg. Fresh simarouba leaves contained 377.90 ± 37.32 mg GAE/g of total phenols (dry basis) and 253.61 ± 45.22 mg Quercetin/g of total flavonoids (dry basis). L*, a* and b* values of fresh simarouba leaves were found to be 39.23 ± 0.42, -5.43 ± 0.56 and 9.67 ± 1.20, respectively, indicating dark green colour of leaves. Quantitative analysis showed 48.709 mg/g of total phenols and 101.19 mg/g of total phenols were presented in leaves of *Simarouba glauca* (Ariharasivakumar *et al.*, 2020).

4.2 Development of Solar-cum-Biomass Energy Hybrid Dryer

Solar-cum-biomass energy hybrid dryer (Plate 4.1) has been developed based on the selection of glazing material and design criteria as described in Section 3.4. Six different greenhouse glazing materials were tested for effective temperature and relative humidity profile.

Table 4.1: Properties of fresh simarouba leaves

Particulars		Fresh leaves
Moisture content (% w.b.)		64.25 ± 0.76
Moisture content (% d.b.)		179.79 ± 5.91
Dry matter (%)		35.75 ± 0.76
1000 leaves weight (kg)		4.4 ± 0.1
Bulk density (kg/m^3)		72.75 ± 4.60
True density (kg/m^3)		1048.98 ± 34.37
Leaf surface area (cm^2)		20.26 ± 2.39
Total phenols (mg GAE/g)		377.90 ± 37.32
Total flavonoids (mg Quercetin/g)		253.61 ± 45.22
Size	Length (cm)	8.07 ± 0.74
	Width (cm)	2.77 ± 0.23
	Thickness (cm)	0.045 ± 0.01
Colour	L*	39.23 ± 0.42
	a*	-5.43 ± 0.56
	b*	9.67 ± 1.20
L* = Lightness of the sample a* = Redness (+) or Greenness (-) of the sample b* = Yellowness (+) or Blueness (-) of the sample		

4.2.1 Effect of different glazing materials on temperature profile inside the solar energy collection chamber

Six different greenhouse glazing material namely, acrylic, EVOH, fibre glass, polycarbonate, polyethylene and PVC were used for the solar energy collection chamber in order to study the variation in temperature and relative humidity profile inside the chamber (Table 4.2). The plastic films; EVOH and polyethylene were 0.12 ± 0.01 mm

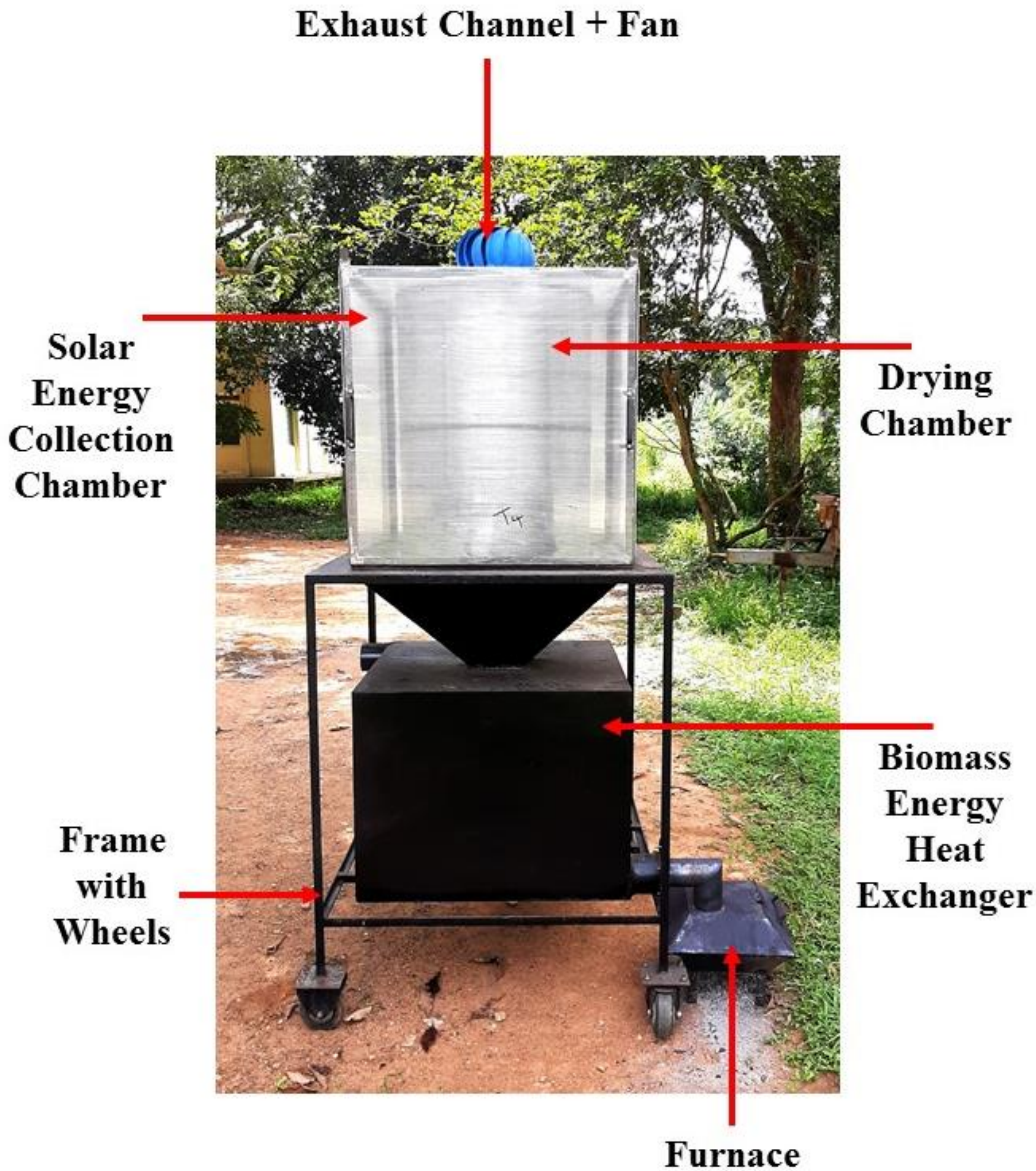


Plate 4.1: Solar-cum-Biomass Energy Hybrid Dryer

thick while the plastic sheets - fibre glass and PVC were of 1.13 ± 0.01 mm thickness. The acrylic sheet was 1.72 ± 0.01 mm thick and the polycarbonate structured sheet was of 3.73 ± 0.01 mm thickness. The highest average temperature recorded during the day was 38.4 ± 2.87 ^oC, in the polycarbonate glazed chamber followed by fibre glass (36.7 ± 2.33 ^oC), acrylic (35.7 ± 2.79 ^oC), PVC (35.5 ± 2.40 ^oC) and EVOH (35.1 ± 2.03 ^oC). The lowest average temperature of 35.0 ± 1.85 ^oC was recorded with polyethylene film. Average day ambient air temperature was 31.3 ± 1.13 ^oC (APPENDIX A). The temperature profile inside different solar energy collection chambers are presented in Figure 4.1. Anil *et al.* (2013) recorded maximum temperature of 40.6 ^oC inside the polycarbonate greenhouse type natural convection dryer.

Table 4.2: Average daily temperature and relative humidity inside solar energy collection chamber of different glazing materials for 20 days

Materials	Temperature (^oC)	Relative Humidity (%)
Acrylic	35.7	28.9
EVOH	35.1	32.4
Fibre Glass	36.7	27.6
Polycarbonate	38.4	25.5
Polyethylene	35.0	34.1
PVC	35.5	30.4
SEM	1.01	1.12
CD at 5%	NS	3.46
C.V. (%)	4.82	6.51

The average of temperature difference between different glazing materials and ambient air was recorded 4.8 ^oC. Koyuncu (2006) reported 5-9 ^oC more temperature of drying air as compared to ambient air for polyethylene sheet. For polycarbonate sheet, the average maximum temperature was 9.4 ^oC more than the average ambient air temperature (33.6 ^oC) at 03:00 p.m. However, the average maximum temperature of 43.1 ^oC for polycarbonate sheet and 34.0 ^oC for ambient air was recorded at 01:30 p.m. Arjoo *et al.* (2017) reported temperature variation of 8-30 ^oC between ambient air and inside temperature of tunnel dryer. The inside temperature was 10 ^oC higher than the ambient temperature for 1 m × 1 m × 1 m polycarbonate covered greenhouse model (Arekornchee *et al.*, 2014). Moreover, Sanusi *et al.* (2013) indicated that temperature difference was higher in direct type dryer as compared to indirect dryers and open sun drying. As the product is directly exposed to the radiation in direct types of solar dryers, losses during transportation of heat and heat exchange losses is reduced as compared to indirect type solar dryers.

4.2.2 Effect of different glazing materials on relative humidity inside the solar energy collection chamber

Relative humidity profile of inside environment for acrylic, EVOH, fibre glass, polycarbonate, polyethylene and PVC glazed chambers were observed with time and temperature (APPENDIX A) and shown in Figure 4.2. The minimum relative humidity of 30.5% was recorded for ambient air at 1:30 p.m. The average ambient relative humidity for the day was 37.5%. Among the different materials, minimum daily average relative humidity of 25.5% was observed for polycarbonate material. It was followed by fibre glass, acrylic, PVC and EVOH with 27.6, 28.9, 30.4 and 32.4% of relative humidity, respectively. The maximum daily average relative humidity was found to be 34.1% inside polyethylene covered environment. Minimum relative humidity (19.5%) was observed for polycarbonate material at 01:30 p. m.

The difference between average relative humidity of polycarbonate and ambient air was 12.0%. Sacilik *et al.* (2006) reported that the difference between the relative humidity inside the solar tunnel covered with polyethylene film and ambient air was 8.7% during experimental time. The result indicated lower value of relative humidity inside atmosphere of solar structure as compared to ambient atmosphere. The relative humidity decreased with time inside the chamber for the first half of the day, further increased during the second half of the day. The decrease in the relative humidity would be caused due to increase in the temperature of ambient air and air inside the chamber (Janjai, 2012).

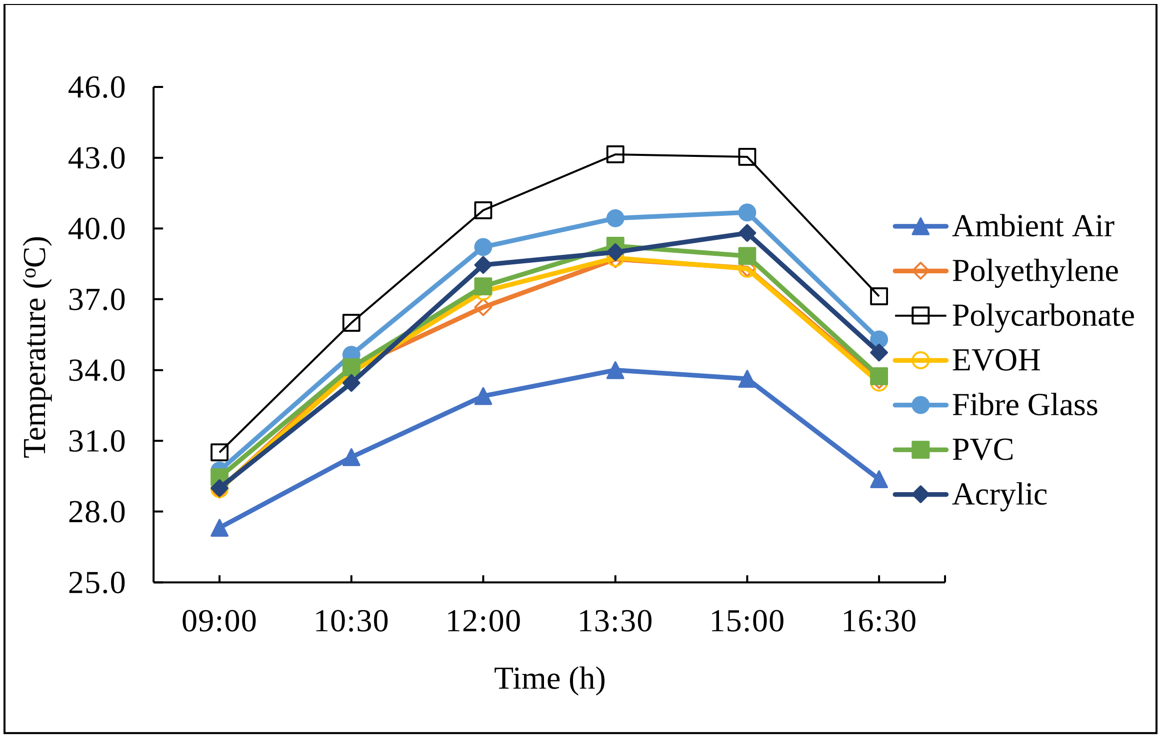


Figure 4.1: Temperature profile inside different solar energy collection chambers

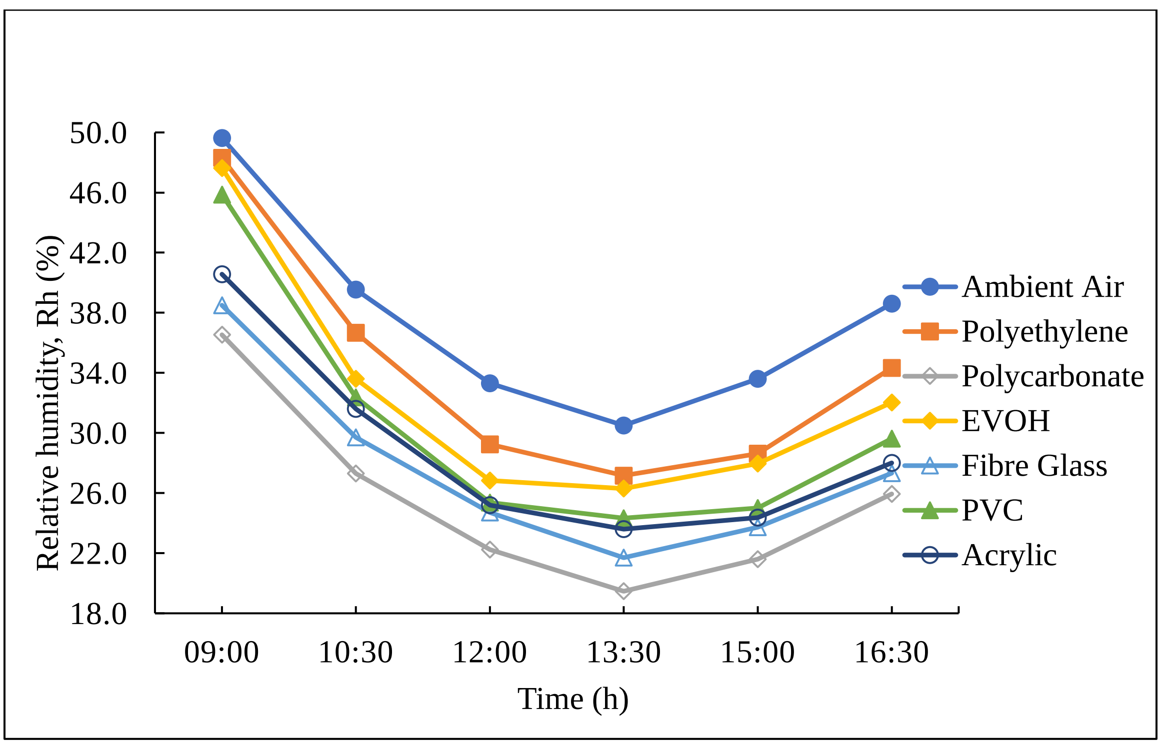


Figure 4.2: Relative humidity profile inside different solar energy collection chambers

The temperature profile was found to be effective for polycarbonate material with 43.1 ^{o}C maximum average temperature and 38.4 ^{o}C daily average temperature. There were 9.1 ^{o}C and 7.2 ^{o}C increase in maximum average temperature and daily average temperature, respectively, for polycarbonate sheet as compare to ambient environment (34.0 ^{o}C and 31.3 ^{o}C, respectively). Similarly, lower relative humidity profile was observed for polycarbonate sheet (19.5% minimum average relative humidity and 25.5% daily average relative humidity) as compare to ambient environment (30.5% minimum average relative humidity and 37.5% daily average relative humidity). Polycarbonate sheet was found to be best glazing material for effective harness of solar radiation. Therefore, polycarbonate sheet was selected as suitable glazing material for fabrication of solar drying unit.

4.2.3 Fabrication of solar-cum-biomass energy hybrid dryer

Solar-cum-biomass energy hybrid dryer was developed using different fabrication materials like aluminium perforated sheet, mild steel (MS) sheets, polycarbonate sheet, MS angle bar, fan (wind turbine) and wheels. Bill of materials used for the development of dryer are tabulated in Table 4.3. Overall dimensions of the developed dryer were 1.0 m x 1.0 m x 2.3 m. The dryer has been designed for a capacity of 15 kg of fresh simarouba leaves. Total energy required for the moisture removal from 15 kg simarouba leaves was 21,303.575 kJ. The components of the solar-cum-biomass energy hybrid dryer are described as below.

4.2.3.1 Solar energy collection chamber

Solar energy collection chamber (Plate 3.4) was made from MS angle bar and polycarbonate sheet. Cubic shaped frame having 80 cm × 80 cm × 80 cm dimensions was made from the MS angle bar. All sides of the chamber were covered with polycarbonate sheet, except bottom side.

4.2.3.2 Drying chamber with exhaust channel

Perforated aluminium sheet (Plate 3.5a) with 3-mm diameter holes in zig-zag pattern was used for the construction of drying chamber and exhaust channel. The dimension of cylindrical shaped drying chamber was 60 cm in diameter with height of 80 cm. A cylindrical shaped exhaust channel was made of 12.5 cm in diameter and 80 cm in height at the centre of the drying chamber. Commercial fan having the wind turbine design was attached at the top of the exhaust channel for air removal.

4.2.3.3 Biomass energy heat exchange unit with plenum chamber

Shell and duct type heat exchange unit with plenum chamber (Plate 3.5d) was fabricated for temperature rise of drying air. The unit was made from 18-gauge MS sheet. Duct was square in cross-section and cuboid shape shell covered the duct. Length of duct was provided in definite pattern for better heat transfer.

Table 4.3: Bill of materials for fabrication of solar-cum-biomass energy hybrid dryer

Material	Size	Requirement
Drying Chamber		
Aluminium perforated sheet	1.88 × 0.8 m	1 piece
Aluminium perforated sheet	0.4 × 0.8 m	1 piece
Aluminium perforated sheet	0.6 m diameter	1 piece
Solar Energy Collection Chamber		
MS angle bar	0.8 m	12 pieces
Polycarbonate sheet	0.8 × 0.8 m	5 pieces
Biomass heat energy exchange system		
Shell		
MS sheet, 18 gauge	0.626 × 0.8 m	4 pieces
MS sheet, 18 gauge	0.8 × 0.8 m	2 pieces
Duct		
MS sheet, 18 gauge	1.2 × 2.4 m (Std. sheet)	2 pieces
Frame		
MS angle bar	1 m	14 pieces
MS sheet, 16 gauge	1 × 1 m	1 piece

Outlet of duct was attached with the inverted pyramid shaped chamber, which further connected with frame. Provisions for inlet and outlet of flue gas were made with the help of circular ports (10 cm diameter) on the shell surface. The orientation of bottom inlet port and top outlet port was designed diagonally opposite to each other. Nut and bolt attachment were provided at inlet of shell to attach biomass furnace.

A) Shell : 80 cm × 80 cm × 62.6 cm

B) Duct : Cross section of 18 cm × 18 cm with 322 cm of length

4.2.3.4 Frame

The frame of the hybrid dryer was fabricated with the help of MS angle bar and wheels were attached to each leg for easy transportation as shown in Plate 4.1. The frame acted as stand for solar energy collection chamber and drying chamber as well as holder for biomass energy heat exchanger. Top of the frame was plated with 16-gauge MS sheet for support and 4 square holes of 5 cm and 7.5 cm each were made to pass the drying air.

4.2.3.5 Working principle of solar-cum-biomass energy hybrid dryer

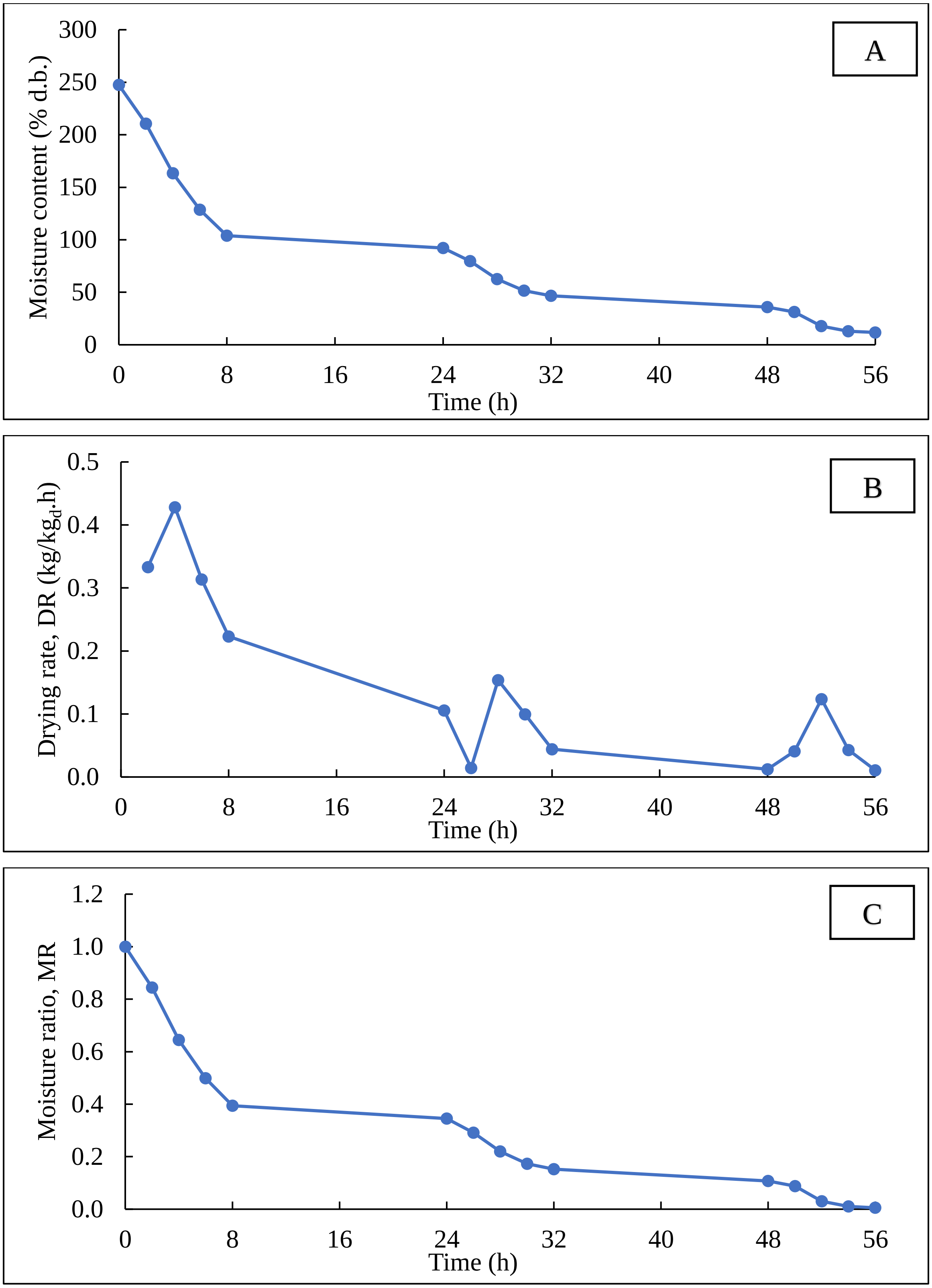
The developed hybrid dryer has three major components: a) Drying chamber with an exhaust channel, b) Solar energy collection chamber and c) Biomass energy heat exchanging unit with plenum chamber. Fresh air enters into the dryer through the inlet port at the bottom of the biomass energy heat exchanging unit shell and passes through the duct system. Then the air from duct enters the solar energy collection chamber through holes made on the connecting platform. In the solar energy collection chamber, due to the transmitted radiation through the glazing material cover (polycarbonate sheet), the air is heated up by absorbed solar energy. The heated drying air reaches the product through perforations made on peripheral surface of the drying chamber and the bulk simarouba leaves loaded in the drying chamber gets dried by heated air. Heated air moves randomly through the porous channels of bulk leafy material and picks up the moisture from the drying material. The air with moisture leaves the drying chamber through the centrally placed perforated aluminium exhaust channel and goes out to environment aided by exhaust fan. The air circulation is purely by natural convection process and there are no mechanically moving parts. During drying operation, no external energy is provided and the operation is generally uninterrupted. The drying of material takes place without any adverse environmental effect and involve almost no operational and maintenance cost. Biomass energy is provided with the help of burning of the fuels in attached furnace in case of insufficient solar energy. Flue gas flows in shell part and heats up the ambient air flowing inside duct of biomass energy heat exchange unit.

4.3 Drying Kinetics of Simarouba Leaves

Six drying methods such as shade drying, sun drying, tray drying, solar drying, biomass drying and solar-cum-biomass energy hybrid drying were used to dry the simarouba leaves. The drying studies were carried out until the final product attained the moisture content around 10% w.b. The drying kinetics of simarouba leaves dried under different methods are presented as follows,

4.3.1 Shade drying of simarouba leaves

Shade drying is one of the traditional drying methods for drying heat sensitive materials such as medicinal herbs. Drying of the simarouba leaves under shade was performed and the moisture loss from leaves at an interval of 2 hours is presented in Figure 4.3. The time required to dry 7.5 kg of leaves was 56 hours under shade drying. Drying rate was observed to be fast during first day, however, next two consecutive days; it was slow as shown in Figure 4.3. Moisture ratio was also observed to be in decreasing order with respect to drying time (Figure 4.3). Drying during afternoon was rapid due to higher temperature as compared to forenoon. During night, the drying rate was found very slow. The average temperature of shaded area was recorded to be 28.5 ^{o}C, which was 3.3 ^{o}C lower as compared to outside atmosphere. Relative humidity of drying area was 9.8% higher than an ambient environment during recording time. Mishra *et al.* (2012) dried *Moringa* leaves under shade for 4 days at a room temperature. The curry leaves were dried at room temperature of 32.5 ± 1 ^{o}C under the shade drying in order to observe quality characteristics (Kenghe *et al.*, 2015).



A: Moisture Content; B: Drying rate; C: Moisture ratio

Figure 4.3: Drying kinetics of simarouba leaves under shade drying method

4.3.2 Sun drying of simarouba leaves

In sun drying, simarouba leaves were exposed to direct sun light from 09:00 a.m. to 05:00 p.m., and moisture loss was recorded at regular intervals. The decrease in moisture content, drying rate and moisture ratio during drying are presented in Figure 4.4. Sun drying was completed within 32 hours for the batch of 7.5 kg leaves. Rapid decrease in drying rate and moisture ratio was observed for starting 8 hours. The drying kinetics was observed to very slow between 8 to 24 hours as the drying samples were withdrawn from drying during night. As drying was resumed on next day during sun shine hours, the rapid drying was observed for another 8 hours. The total drying time in sun drying was 32 hours including 16 hours of non-recording hours at night. The drying time in sun drying was reduced by 24 hours as compared to shade drying. The average ambient temperature and relative humidity during recoding time was observed to be 30.2 ^{o}C and 29.2%, respectively. The maximum temperature (35.7 ^{o}C) and the minimum relative humidity (22.8%) were observed at 01:00 p.m. Kamble *et al.* (2015) reported 15 hours drying time in open sun drying of tomato slices with a maximum ambient air temperature of 42.1 ^{o}C. Time required for drying *Hibiscus cannabinus* was reported 72 hours by Garti *et al.* (2018).

4.3.3 Tray drying of simarouba leaves

Tray drying was performed at 55 ^{o}C to observe the drying kinetics of the simarouba leaves and the results are presented in Figure 4.5. Uniform decrease in moisture was observed at regular intervals due to constant drying temperature. The amount of moisture removal was observed to be higher during initial stage. The drying time was found to be 14 h to reduce the moisture content from 64% to 8%. Curry leaves were dried at 65 ^{o}C in tray dryer as reported by Kenghe *et al.* (2015). Drying temperature of 60 ^{o}C was recommended for drying of dill and parsley leaves with drying time of around 350 minutes (Doymaz *et al.*, 2006).

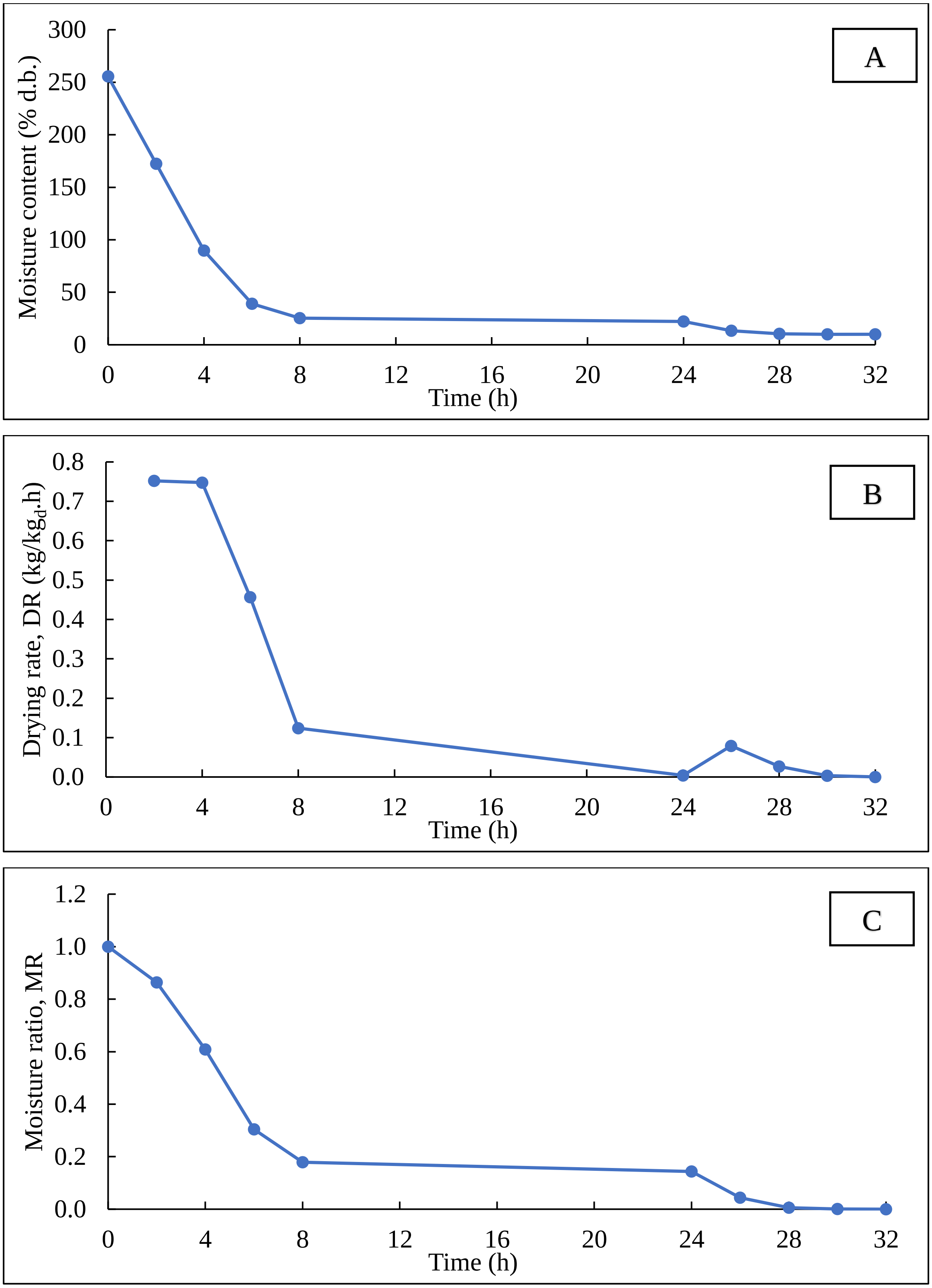
4.3.4 Solar drying of simarouba leaves

Solar drying of simarouba leaves was carried out using developed hybrid dryer. In this method, however, only solar radiation effect was considered for drying. A batch of 7.5 kg sample in bulk was dried and moisture evaporated with time was recorded. The recording duration was considered from 09:00 a.m. to 07: 00 p.m. to observe the effect of post sun shine hours inside the drying chamber. The change in moisture content, drying rate and moisture ratio during solar drying are presented in Figure 4.6. Rapid drying was observed for initial 10 hours followed by lower drying rate during non-recording hours from 10 - 24 h. After resuming of drying on next day, the drying was further continued for another 10 h to accomplish desired moisture level in the dried leaves. The total drying time, therefore, observed to be 34 hours including 14 h non recording period at night.

A maximum temperature (41.1 ^{o}C) and the minimum relative humidity of drying air (19.5%) were observed at 01:00 p.m. An average temperature of drying air (34.8 ^{o}C) in solar dryer was found 5.9 ^{o}C higher than an ambient air temperature (28.9 ^{o}C) as shown in Figure 4.7. Highest temperature was observed for drying air followed by exhaust air and ambient air, respectively. Average temperature difference between drying air and exhaust air was 3.2 ^{o}C. Relative humidity of exhaust air was observed higher than drying air but lower than ambient air. Minimum relative humidity of ambient air was recorded as 27.6%. The temperature difference of 5 ^{o}C to 26 ^{o}C between ambient air and drying air during solar drying of different products was reported by Arjoo *et al.* (2017); Padmapani *et al.* (2019); Prasad *et al.* (2006) and Sengar *et al.* (2018). Akpinar (2010) observed the temperature of ambient air, drying air and exhaust air in same manner for solar drying. Kamble *et al.* (2015) reported 12.5 hours thin layer drying time for 10 kg of tomato slices at 52.63 ^{o}C to achieve the final moisture content of 8.97%.

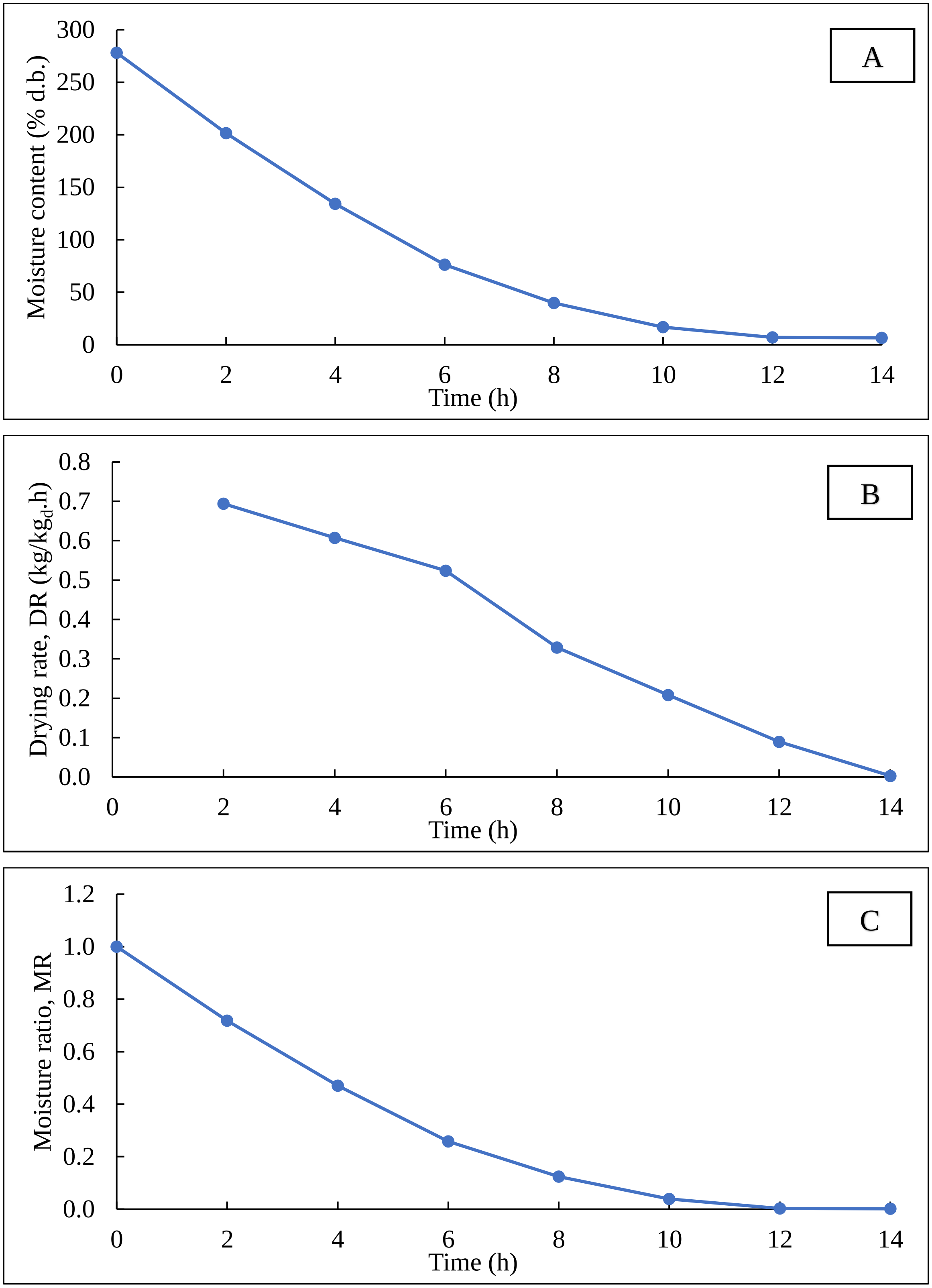
4.3.5 Biomass drying of simarouba leaves

Biomass drying was carried out to dry simarouba leaves using briquettes as a heat source. Briquettes were fed continuously at feed rate of 2 kg/h to raise the temperature of drying air and moisture losses of leaves with time were recorded and presented in Figure



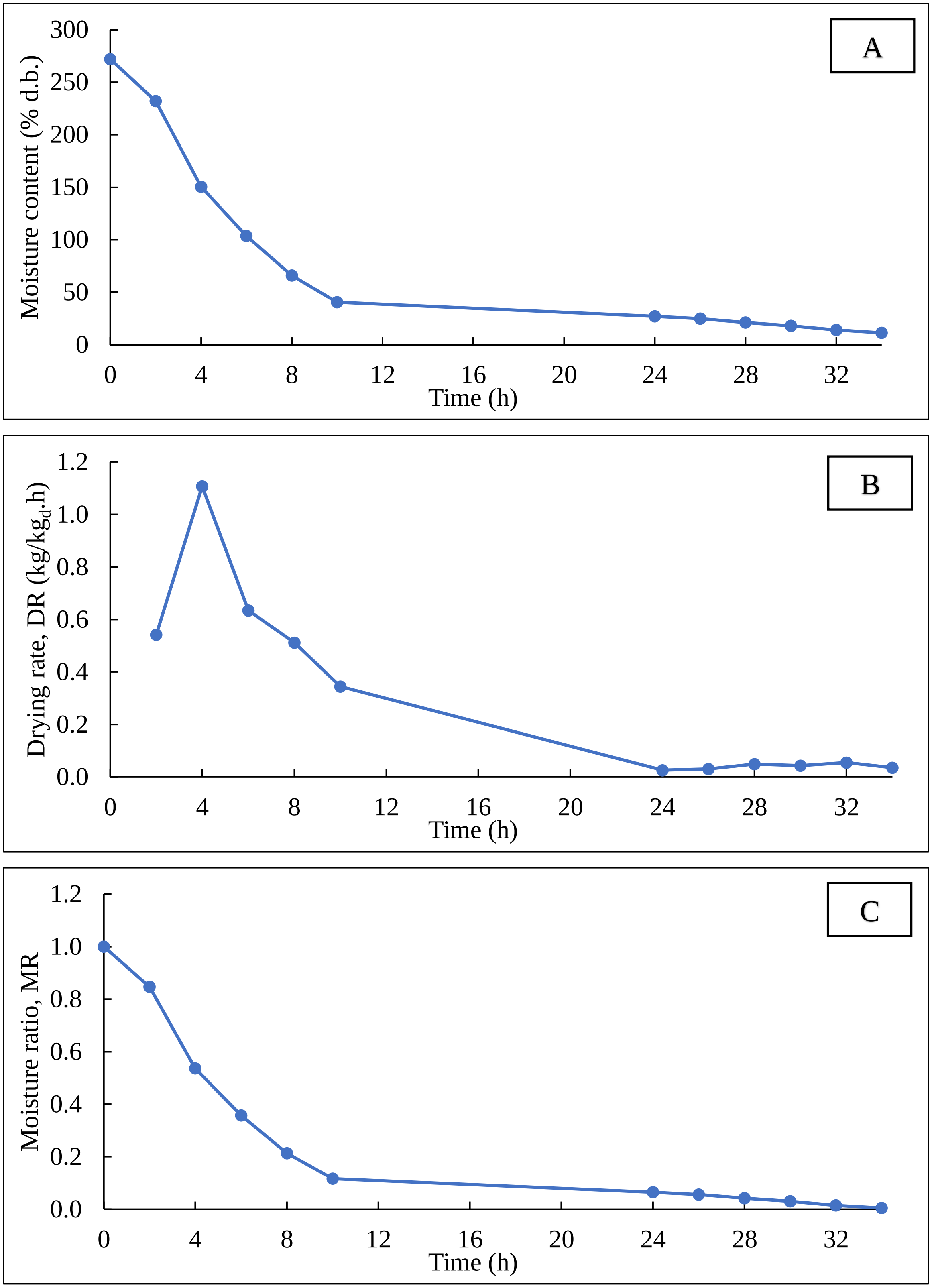
A: Moisture Content; B: Drying rate; C: Moisture ratio

Figure 4.4: Drying kinetics of simarouba leaves under sun drying method



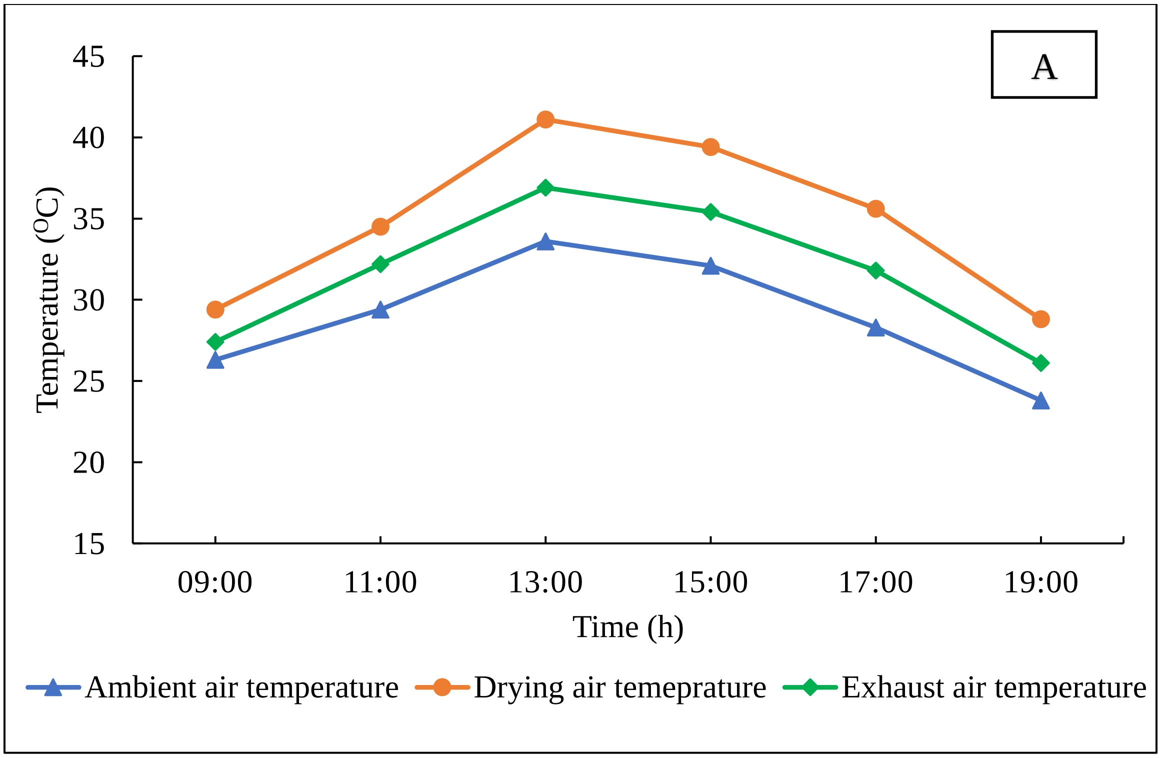
A: Moisture Content; B: Drying rate; C: Moisture ratio

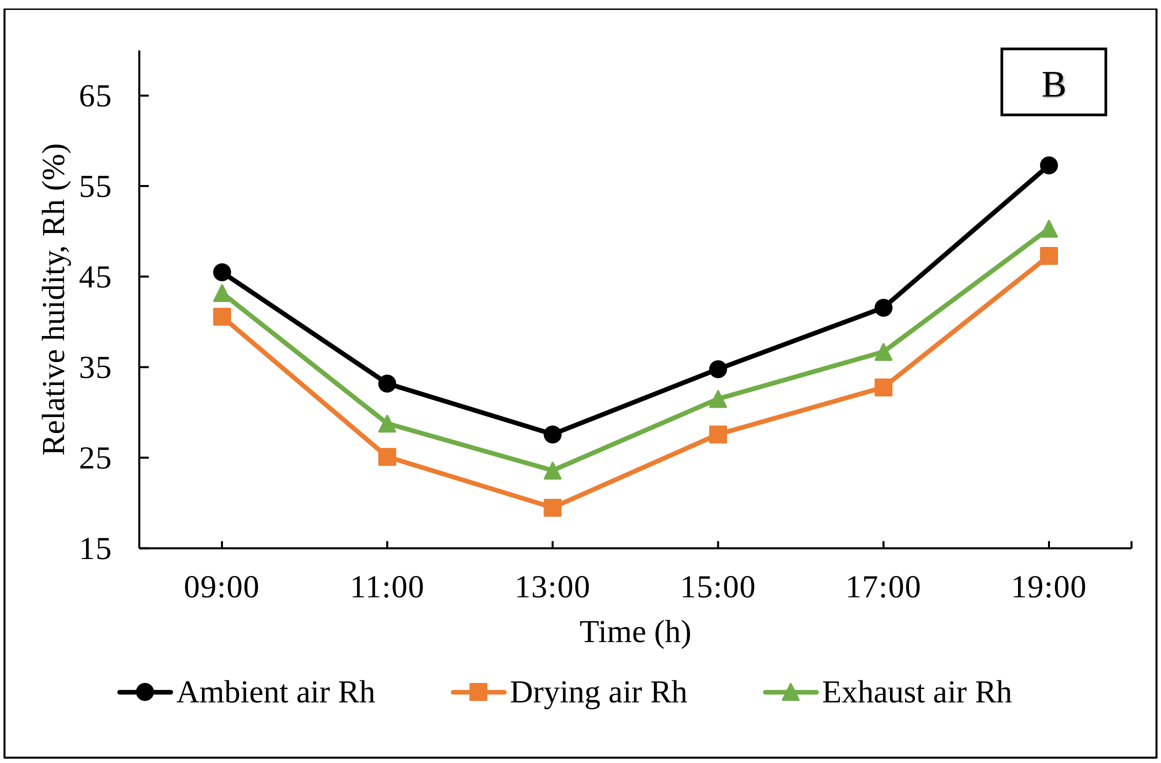
Figure 4.5: Drying kinetics of simarouba leaves under tray drying method



A: Moisture Content; B: Drying rate; C: Moisture ratio

Figure 4.6: Drying kinetics of simarouba leaves under solar drying method





A: Temperature; B: Relative humidity

Figure 4.7: Temperature and relative humidity profile of air during solar drying of simarouba leaves

4.8. Biomass drying method required 18 h to dry the leaves. The decrease in both drying rate and moisture ratio are also presented in Figure 4.8. It was observed that drying rate decreased with drying time. An average temperature of the drying air observed to be almost constant (45.8 ± 0.87 ^{o}C) during operation. However, lag period of 30 minutes was observed to attain the required drying temperature after combustion of briquettes. Similar to tray dryer, the uniformity in drying kinetics was also observed in biomass drying method.

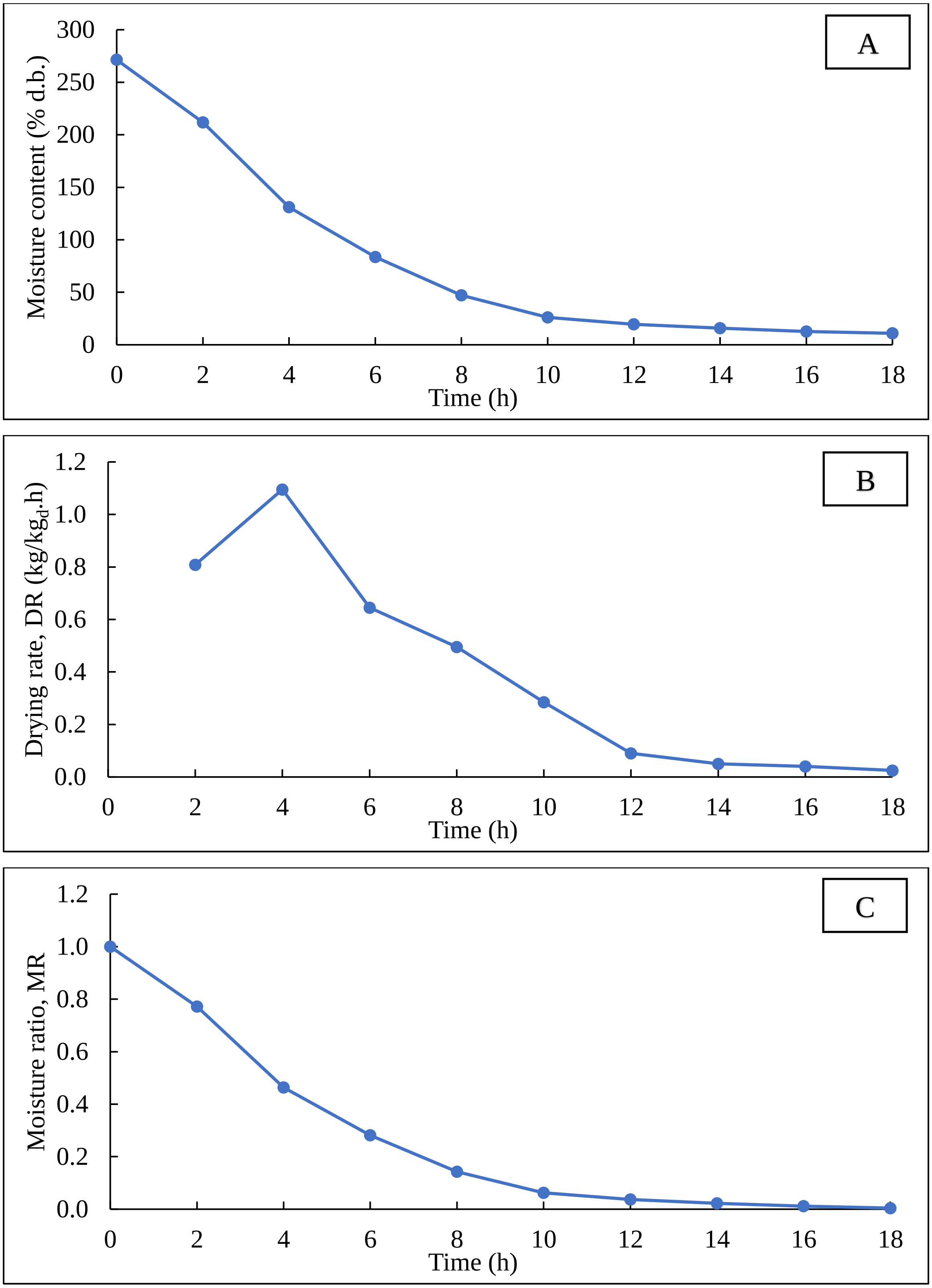
An average relative humidity of drying air was recorded to be 22.1%, lower than an ambient environment (49.2%). Maximum temperature and minimum humidity of ambient air were recorded as 34.4 ^{o}C and 22.5%, respectively. The average temperature difference between drying air and exhaust air was 5.6 ^{o}C, which decreased with time (Figure 4.9). Relative humidity of exhaust air was observed to be higher than drying air, thus indicating moisture removal during drying which was carried from the product to the environment. Geramitchioski *et al.* (2011) reported that about 60 ^{o}C of drying air temperature could be obtained by combusting 4 kg wood briquettes per hour. Andrew *et al.* (2013) reported that the higher drying temperature could be obtained by using biomass as heating source during night. Drying air temperature was reported as 10 to 35 ^{o}C higher than the ambient air. The maximum temperature of drying air could be raised up to 60 ^{o}C by using biomass burner with thermal back-up unit for gas to gas heat exchanger (Yassen *et al.*, 2013).

4.3.6 Solar-cum-biomass energy hybrid drying of simarouba leaves

Solar-cum-biomass energy hybrid drying was carried out on simarouba leaves to overcome the limitations of solar drying and biomass drying. Continuous drying was ensured between 07:00 a.m to 03:00 a.m in which solar energy was ensured during day time between 09:00 a.m. to 05:00 p.m. and the biomass energy was supplied through combustion of briquettes during non-sun shine hours (07:00 a.m. - 09:00 a.m. and 05:00 p.m - 03:00 a.m.) at feed rate of 2 kg/h. Moisture loss, drying rate and moisture ratio for hybrid drying are presented in Figure 4.10. The total drying time required for drying of simarouba leaves using hybrid drying method was found to be 20 h. The average temperature of drying air during initial period between 07:00 a.m. and 09:00 a.m. was observed to be 41.1 ^{o}C due to effect of biomass energy. The average temperature of drying air between 09:00 a.m. and 05:00 p.m. was observed to be 40.7 ^{o}C due to solar radiation effect. An average temperature of 46.1 ^{o}C was observed for further period between 05:00 p.m. and 03:00 a.m. due to biomass energy source.

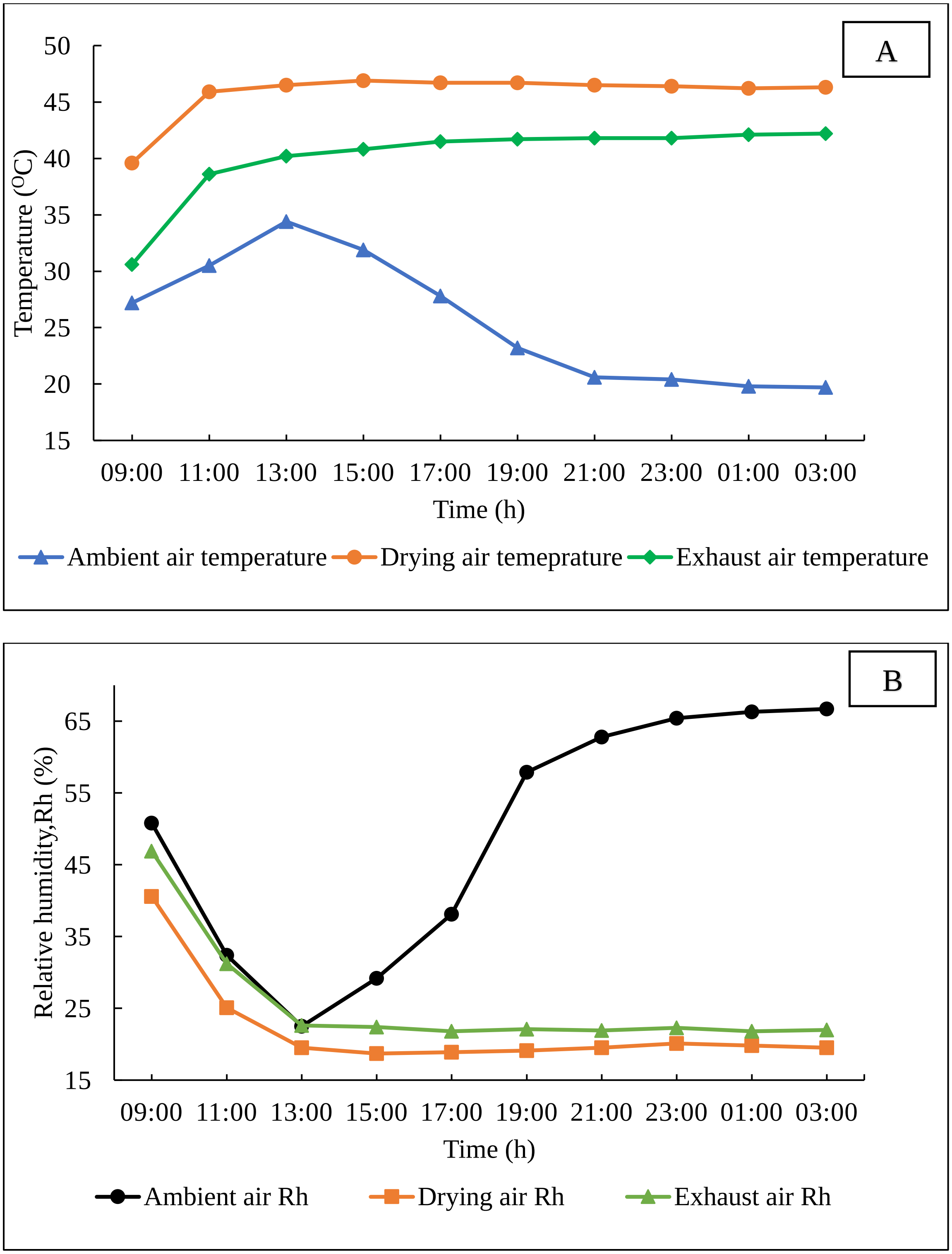
An average temperature (43.2 ^{o}C) and average relative humidity (23.7%) for hybrid drying method for overall drying period are presented in Figure 4.11. Average temperature and relative humidity for ambient air were recorded as 25.3 ^{o}C and 50.1%, respectively. The average temperature gradient between drying air and ambient air was observed to be 17.9 ^{o}C; whereas 26.4% of gradient was observed in average relative humidity. The relative humidity of exhaust air was observed higher than the drying air and the difference between relative humidity of drying air and exhaust air decreased with time. Approximately, 30.7% of total moisture was removed in 8 h by solar drying and remaining 69.3% was removed in 12 h with the help of biomass energy. Bena and Fuller (2002) reported that 47% of moisture would be removed by solar energy. Moisture removal by solar energy would be depended on the intensity of the solar radiation. Okoroigwe *et al.* (2013) reported that the drying with the combination of solar and biomass heat for day and night would improve the dryer efficiency.

Drying studies of simarouba leaves under hybrid drying technique was compared with shade drying, sun drying, tray drying, solar drying and biomass drying (Table 4.4). In all drying methods, leaf moisture content was reduced from 64% to about 10% w.b. Average drying air temperature for shade, sun, tray, solar, biomass and hybrid drying were found to be 28.5 ± 0.91, 30.2 ± 1.80, 55.0 ± 0.20, 34.8 ± 0.66, 45.8 ± 0.87 and 43.2 ± 1.02, respectively. The drying air temperature in hybrid drying method was found significantly higher than shade, sun and solar drying methods, but significantly lower than tray drying and biomass drying. Similar trend was observed in drying time. Drying time in hybrid drying (20 h) was found to be shorter compare to sun drying (32 h), shade drying (56 h), solar drying (34 h) and longer than tray drying (14 h) and biomass (18 h) drying. Drying time for hybrid dryer was not significantly lower than biomass drying. It was observed that drying time could be reduced by 64% in hybrid drying as compared to



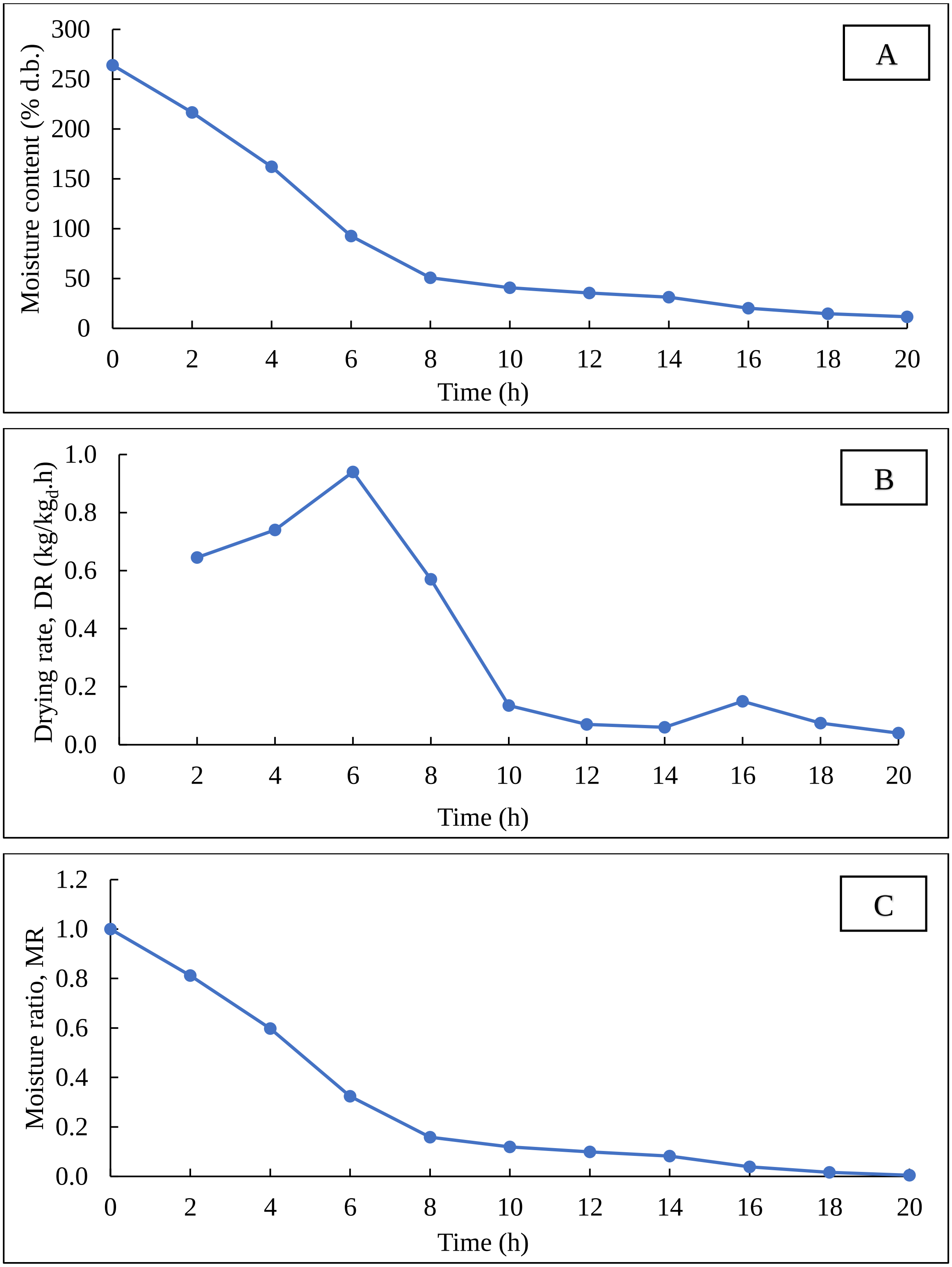
A: Moisture Content; B: Drying rate; C: Moisture ratio

Figure 4.8: Drying kinetics of simarouba leaves under biomass drying method



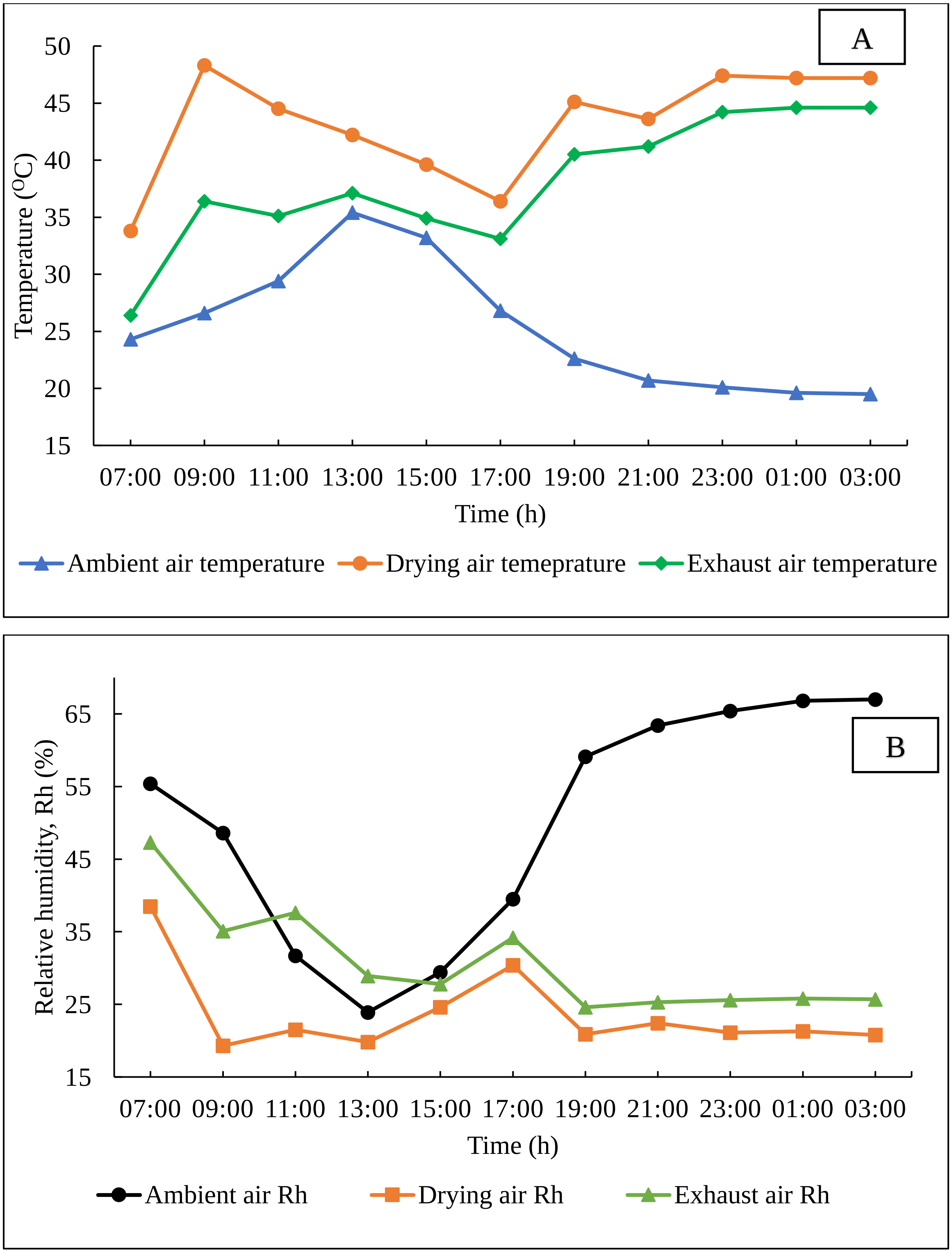
A: Temperature; B: Relative humidity

Figure 4.9: Temperature and relative humidity profile of air during biomass drying of simarouba leaves



A: Moisture Content; B: Drying rate; C: Moisture ratio

Figure 4.10: Drying kinetics of simarouba leaves under solar-cum-biomass energy hybrid drying method



A: Temperature; B: Relative humidity

Figure 4.11: Temperature and relative humidity profile of air during solar-cum-biomass energy hybrid drying of simarouba leaves

shade drying. Kenghe *et al.* (2015) reported that tray drying reduced 27% of time for curry leaves as compared to shade and sun drying. Sacilik *et al.* (2006) observed 26.9% less time for solar drying of tomato slices as compared to sun drying. Yahya (2016) reported the solar assisted heat pump dryer for red chillies saved 82% drying time as compared to open sun drying. The drying time for rose and marigold flowers in solar dryer was reduced by 65% and 70% than open sun drying, respectively (Padmapani *et al.*, 2019).

The drying rate was highest for tray trying (0.3307 ± 0.008) and lowest for shade drying (0.0810 ± 0.002) as shown in Figure 4.12. The drying rate in solar drying and biomass drying were found to be 0.1318 ± 0.001 $kg/kg_d.h$ and 0.2536 ± 0.004 $kg/kg_d.h$, respectively. Drying rate in hybrid drying (0.2254 ± 0.004 $kg/kg_d.h$) which had integrated approach of both solar and biomass energy was significantly lower than biomass drying and significantly higher than solar drying. However, drying rate in all methods significantly differ from each other. The rate of drying for yam chips was recorded as 0.0142 kg/h for hybrid drying and 0.00732 kg/h for solar drying (Okoroigwe *et al.*, 2013). Yahya (2016) observed 1.57 kg/h of drying rate in case of yam chips drying in solar assisted heat pump dryer.

The final moisture content of simarouba leaves dried under different methods is presented in Table 4.4. In this study, the target was to achieve the final moisture content to around 10%, however, in few methods, final moisture content of dried leaves was observed slightly higher than 10%. This may be due to withdrawal of drying samples at specific interval during end of the drying. However, no significant difference was observed in the values of final moisture content of dried leaves obtained from different drying methods. The final moisture content of simarouba leaves was reported to be approximate 10% under shade drying (Manasa *et al.*, 2019). Sengar *et al.* (2018) reported that moisture content of the leaves of Heena, Neem, Sargava and Tulsi could be achieved below 10% at 46.6 ^{o}C of solar tunnel drying.

The heat utilization factor (HUF) was calculated only for bulk drying methods and the results are presented in Table 4.4. HUF was found 0.54, 0.33 and 0.40 for solar, biomass and hybrid drying, respectively. HUF in hybrid drying was significantly differing from solar drying, however, it was non-significant compare to biomass drying. HUF was reported to be 0.57 during drying of potatoes in developed solar cooker cum dryer (Sayyad *et al.*, 2015).

Table 4.4: Drying parameters of simarouba leaves under different drying methods

Treatment	Average drying air temperature (°C)	Drying Time (h)	Drying Rate (kg/kg$_d$.h)	Final MC (% w.b.)	HUF
Shade Drying	28.5^e ± 0.91	56^a	0.0810^f ± 0.002	10.38^a ± 1.90	-
Sun Drying	30.2^e ± 1.80	32^b	0.1457^d ± 0.003	9.06^a ± 0.27	-
Tray Drying	55.0^a ± 0.20	14^d	0.3307^a ± 0.008	7.56^a ± 0.47	-
Solar Drying	34.8^d ± 0.66	34^b	0.1318^e ± 0.001	10.57^a ± 0.47	0.54^a
Biomass Drying	45.8^b ± 0.87	18^{cd}	0.2536^b ± 0.004	9.83^a ± 0.45	0.33^b
Hybrid drying	43.2^c ± 1.02	20^c	0.2254^c ± 0.004	10.71^a ± 0.51	0.40^b
SEM	0.59	1.33	0.003	0.505	0.02
CD at 5%	1.83	4.11	0.008	1.557	0.08
C.V. (%)	2.61	7.96	2.242	9.035	9.62

The total cost of fabrication of the dryer excluding furnace was Rs. 27,395 and the costing was given in APPENDIX B. Total cost of hybrid dryer was very low as compare to tray dryer (~Rs. 60,000) for the same capacity. Briquettes were used at the feed rate of 2 kg/h for 12 h and 18 h in hybrid drying and biomass energy drying to heat the drying air, respectively. Therefore, the total quantity of briquettes used to produce dried leaves was 24 kg and 36 kg in hybrid drying and biomass energy drying, respectively. About 33% fuel requirement in the form of biomass briquettes was cut down in hybrid drying as compare to biomass drying. Dhanushkodi *et al.* (2015) investigated cycle cost of cashew drying in a combination dryer and reported that the initial investment on solar, biomass and combined dryers would be Rs. 61,732, Rs.48,940 and Rs. 72,972, respectively.

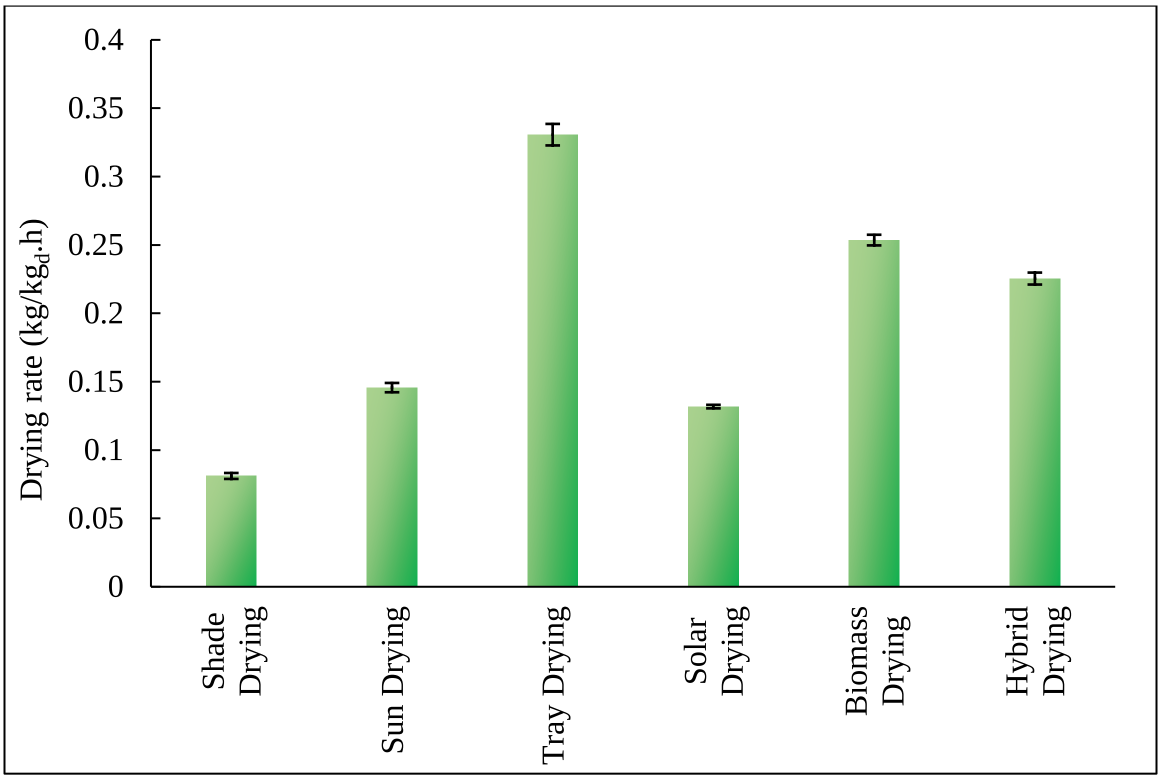


Figure 4.12: Drying rate for simarouba leaves dried under different methods

4.4 Effect of Different Drying Methods on Colour of Dried Leaves.

The L*, a* and b* colour values of fresh leaves were 39.23 ± 0.42, -5.43 ± 0.56 and 9.67 ± 1.20, respectively. The L* value for different drying methods were in range of 56.63 to 62.02 (Table 4.5). Higher value of L* indicated the lighter colour of dried leaves as compare to fresh leaves. Colour values a* and b* indicated the green and yellow colour of the leaves, respectively. In all drying methods, green colour was retained in dried leaves as similar to green colour of fresh leaves with slight lightness.

Table 4.5: Colour values of simarouba leaves dried under different methods

Particulars	Colour			ΔE*
	L*	a*	b*	
Shade drying	59.17^{b} ± 1.87	-5.63^{b} ± 0.35	21.04^{d} ± 0.39	23.00^{b} ± 1.96
Sun drying	62.02^{a} ± 0.66	-7.99^{a} ± 0.20	28.94^{a} ± 0.66	29.97^{a} ± 1.20
Tray drying	56.19^{c} ± 0.57	-6.41^{b} ± 0.25	27.08^{b} ± 0.22	24.35^{b} ± 1.01
Solar drying	61.26^{a} ± 0.80	-7.66^{a} ± 0.34	28.45^{a} ± 0.64	29.04^{a} ± 1.71
Biomass drying	56.63^{c} ± 0.97	-6.05^{b} ± 0.19	26.21^{c} ± 0.07	24.04^{b} ± 0.36
Hybrid drying	58.77^{b} ± 1.64	-6.67^{b} ± 0.23	28.27^{a} ± 0.26	27.03^{a} ± 0.77
SEM	0.674	0.154	0.249	0.74
CD at 5%	2.077	0.476	0.767	2.29
C.V. (%)	1.978	3.974	1.620	4.193
L* = Lightness of the sample a* = Redness (+) or Greenness (-) of the sample b* = Yellowness (+) or Blueness (-) of the sample				

Yellowing of leaves was observed during drying for all methods. Green colour retained in hybrid drying was not significantly different from shade drying, tray drying and biomass drying, however it differed from sun and solar drying methods. The significant change in b* value of dry leaves were observed. Higher b* value of dried leaves was observed for sun drying followed by solar drying and hybrid drying, however, no significant change was observed. Lower b* value was observed for shade drying followed by biomass drying and tray drying, but there was significant change in b* value indicated change in yellow colour of the dried leaves. ΔE* value indicated the total colour change of the dried leaves as compare to fresh leaves. Lower ΔE* value (23.00 ± 1.96) was observed for shade dried leaves whereas higher value was observed for sun dried leaves (29.97 ± 1.20). No significant change was observed in ΔE* values of leaves dried under sun, solar and hybrid drying. Similarly no significant change was observed in ΔE* values of leaves dried under shade, tray and biomass drying.

4.5 Effect of Drying on Phytochemical Properties of Simarouba Leaves.

Phytochemical properties like total phenols and total flavonoids of the dried leaves obtained from different drying methods were measured and expressed in dry basis as shown in Table 4.6. The fresh leaves contained 377.90 ± 37.32 mg GAE/g of total phenols and 253.61 ± 45.22 mg Quercetin/g of total flavonoids as decried earlier.

Table 4.6: Phytochemical properties of simarouba leaves dried under different drying methods

Treatment	Total phenols (mg GAE/g)	Total flavonoids (mg Quercetin/g)
Shade Drying	306.20^{a} ± 27.06	198.14^{a} ± 12.61
Sun Drying	206.81^{a} ± 22.65	139.39^{a} ± 47.93
Tray Drying	231.56^{a} ± 19.39	140.79^{a} ± 12.69
Solar Drying	254.97^{a} ± 43.58	152.91^{a} ± 25.03
Biomass Drying	275.48^{a} ± 22.73	193.01^{a} ± 13.77
Hybrid drying	282.10^{a} ± 35.30	194.87^{a} ± 12.69
SEM	17.133	14.132
CD at 5%	52.792	43.544
C.V. (%)	11.435	14.411

Total phenols of dried leaves ranged between 206.81 ± 22.65 and 306.20 ± 27.06 mg GAE per gram of dried leaves, and total phenols content was ranged between 139.3± 47.93 and 194.87 ± 12.69 mg Quercetin/g of dried leaves. Both total phenols and total flavonoids were highest for shade drying followed by hybrid drying, biomass drying, solar drying, tray drying and sun drying. Higher retention in phytochemical values may be due to lower photo-oxidation and lower temperature under shade. The photo-oxidation in sun drying and the higher temperature in tray drying would have resulted lower retention of phytochemical properties in dry leaves. It was observed that there was no significant difference in total phenols of leaves dried under all drying methods. Similarly, significant difference was not observed in total flavonoids values of dried leaves.

Simarouba leaves dried under hybrid drying method retained about 74.65% and 76.84% of total phenols and total flavonoids, respectively, as compare to fresh leaves. Total phenols of 102.3 ± 0.0027 mg/g GAE was reported for simarouba leaves by Gurupriya *et al.*, 2017. Total phenols and total flavonoids of fresh simarouba leaves were reported to be 151.07 ± 11.05 and 288.99 ± 27.08 mg GAE/g, respectively, whereas for shade dried leaves, these values were reported as 88.03 ± 12.00 and 102.84 ± 4.00 mg Quercetin/g, respectively (Manasa *et al*., 2019).

V SUMMARY AND CONCLUSION

Simarouba (*Simarouba glauca*) is a multi-purpose evergreen tree, commonly known as 'Laxmitaru' or 'Paradise tree'. Simarouba leaves contain several pharmaceutical properties like anticancer, antiulcer, antibacterial, anti-inflammatory, antifungal, antimicrobial, etc. Simarouba leaves are rich source of important phytochemicals such as phenols, flavonoids and antioxidants. Now-a-days, simarouba leaves are gaining attention in the field of medicine due to their rich phytochemical properties. Drying of simarouba leaves is essential prior to extraction of different phytochemicals.

Solar-cum-biomass energy hybrid dryer (Hybrid dryer) is an integration of both solar dryer and biomass fired dryer, which gives advantages in enhancing drying efficiency, reduction in losses, control over quality and reduction in operational time. Hybrid dryers are more energy efficient in non-electrified rural areas. Hybrid drying method is required for drying of products during unfavourable weather condition. Very little work has been reported on development of dryers for effective utilization of both solar and biomass energies in an integrated system. Therefore, the present study has been undertaken to develop solar-cum-biomass energy hybrid dryer for drying simarouba leaves.

Solar-cum-biomass energy hybrid dryer was developed jointly in ICAR-AICRP on Post Harvest Engineering and Technology (Bangalore Centre) and Department of Agricultural Engineering, University of Agricultural Sciences, Bangalore. The different properties of simarouba leaves were determined prior to dryer design. Six different greenhouse glazing materials (Acrylic, EVOH, Fibre glass, Polycarbonate, Polyethylene and PVC) were evaluated for effective temperature and relative humidity profile. Dryer was designed and developed for utilising both solar and biomass energy. Drying kinetics during drying of simarouba leaves were studied for hybrid drying and compared with other methods like shade drying, sun drying, tray drying, solar drying and biomass drying. Drying and other characteristics like drying temperature, drying time, drying rate, heat utilization factor and fabrication cost of hybrid dryer, final moisture content, colour and phytochemical properties of leaves dried under hybrid drying were determined and compared with other methods.

The results of the aforesaid study can be summarized as follows:

- Fresh simarouba leaves contained 64.25±0.76% of moisture, 377.90 ± 37.32 mg GAE/g of total phenols (dry basis) and 253.61 ± 45.22 mg Quercetin/g of total flavonoids (dry basis).

- Temperature profile was found effective for polycarbonate material with 43.1 ^{o}C maximum average temperature and 38.4 ^{o}C daily average temperatures. There were 9.1 ^{o}C and 7.2 ^{o}C increase in maximum average temperature and daily average temperature, respectively, for polycarbonate sheets as compared to ambient environment. Lower relative humidity profile was observed for polycarbonate sheets as compared to ambient environment. Polycarbonate sheet was found to be best glazing material for effective harness of solar radiation.

- Solar-cum-biomass energy hybrid dryer was developed in University of Agricultural Sciences, Bangalore based on properties of simarouba leaves, selection of glazing materials and other design criteria. The major components were solar energy collection chamber, drying chamber with exhaust channel and fan, biomass energy heat exchanging unit with plenum chamber,furnace and main frame with wheels.

- Average drying air temperature for shade, sun, tray, solar, biomass and hybrid drying were found to be 28.5 ± 0.91 ^{o}C, 30.2 ± 1.80 ^{o}C, 55.0 ± 0.20 ^{o}C, 34.8 ± 0.66 ^{o}C, 45.8 ± 0.87 ^{o}C and 43.2 ± 1.02 ^{o}C, respectively. In hybrid drying, an average temperature gradient between drying air and ambient air was 17.9 ^{o}C; whereas 26.4% of gradient was observed in average relative humidity. Drying air temperature in hybrid drying was significantly higher than shade drying sun drying and solar drying.

- Drying time in hybrid drying (20 h) was found to be shorter compared to sun drying (32 h), shade drying (56 h), solar drying (34 h) and longer than tray drying (14 h) and biomass (18 h) drying. Drying time could be reduced by 64% in hybrid drying as compared to shade drying.

- The drying rate was highest for tray trying (0.3307 ± 0.008) and lowest for shade drying (0.0810 ± 0.002). Drying rate in hybrid drying (0.2254 ± 0.004 $kg/kg_d.h$) was significantly lower than biomass drying and significantly higher than solar drying.
- Final moisture content of simarouba leaves dried under hybrid drying was around 10%. Approximately, 30.7% of total moisture was removed in 8 h by solar drying and remaining 69.3% was removed in 12 h with the help of biomass energy.
- The heat utilization factor was found 0.54, 0.33 and 0.40 for solar, biomass and hybrid drying, respectively. Total cost of hybrid dryer (~Rs. 27,395) was very low as compare to tray dryer (~Rs. 60,000) for the same capacity. About 33% fuel requirement in the form of biomass briquettes was cut down in hybrid drying as compared to biomass drying.
- In all drying methods, green colour was retained in dried leaves almost similar to green colour of fresh leaves with slight lightness, however, yellowing of leaves was observed in all methods. Lower ΔE^* value (23.00 ± 1.96) was observed for shade dried leaves whereas higher value was observed for sun dried leaves (29.97 ± 1.20). No significant change was observed in ΔE^* values of leaves dried under sun, solar and hybrid drying. Similarly no significant change was observed in ΔE^* values of leaves dried under shade, tray and biomass drying.
- Total phenols of dried leaves ranged between 206.81 ± 22.65 and 306.20 ± 27.06 mg GAE per gram of dried leaves, and total phenols content was ranged between 139.3± 47.93 and 194.87 ± 12.69 mg Quercetin/g of dried leaves. Both total phenols and total flavonoids were highest for shade drying followed by hybrid drying, biomass drying, solar drying, tray drying and sun drying. No significant difference was observed in phytochemical properties of leaves dried under all six methods. Simarouba leaves dried under hybrid drying method retained about 74.65% and 76.84% of total phenols and total flavonoids, respectively, as compared to fresh leaves.

The results of the aforesaid study lead to the following conclusion.

Polycarbonate sheet would be best glazing material for effective harness of solar energy in solar-cum-biomass energy hybrid dryer. The developed hybrid drier could be used for drying medicinal herbs like simarouba leaves in non- electrified areas.

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APPENDICES

APPENDIX A

DRYING DATA DURING SELECTION OF GLAZING MATERIALS

Air properties inside the chambers as well as ambient for February, 2020.

[A] Ambient air

Time, t (h)	Temperature, T (°C)	Relative Humidity, Rh (%)
9:00	27.3	49.6
10:30	30.3	39.5
12:00	32.9	33.3
13:30	34.0	30.5
15:00	33.6	33.6
16:30	29.4	38.6

[B] Acrylic

Time, t (h)	Temperature (°C)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	29.3	28.9	28.8	40.6
10:30	33.6	33.4	33.3	31.6
12:00	38.7	38.5	38.2	25.2
13:30	39.3	38.9	38.8	23.6
15:00	40.1	39.8	39.5	24.4
16:30	35.0	34.7	34.5	28.0

[C] EVOH

Time, t (h)	Temperature (ºC)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	29.2	28.9	28.7	47.6
10:30	34.2	33.8	33.7	33.6
12:00	37.5	37.4	37.2	26.8
13:30	38.9	38.7	38.6	26.3
15:00	38.7	38.2	38.0	28.0
16:30	33.6	33.4	33.4	32.0

[D] Fibre glass

Time, t (h)	Temperature (ºC)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	30.2	29.7	29.3	38.5
10:30	35.1	34.5	34.4	29.7
12:00	39.5	39.1	39.0	24.7
13:30	39.4	41.2	40.8	21.7
15:00	40.8	40.8	40.5	23.7
16:30	35.5	35.3	35.2	27.3

[E] Polycarbonate

Time, t (h)	Temperature (ºC)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	30.7	30.4	30.4	36.5
10:30	36.3	36.0	35.7	27.3
12:00	40.9	40.7	40.7	22.2
13:30	43.5	43.1	42.8	19.5
15:00	43.4	42.9	42.7	21.6
16:30	37.4	37.1	36.8	25.9

[F] Polyethylene

Time, t (h)	Temperature (°C)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	29.3	28.8	28.7	48.3
10:30	34.3	34.0	33.9	36.7
12:00	36.9	36.6	36.4	29.2
13:30	38.8	38.7	38.5	27.2
15:00	38.6	38.2	38.2	28.6
16:30	33.8	33.6	33.4	34.3

[G] PVC

Time, t (h)	Temperature (°C)			Relative Humidity, Rh (%)
	Top, T_1	Centre, T_2	Bottom, T_3	
9:00	29.5	29.4	29.5	45.9
10:30	34.3	34.1	34.0	32.4
12:00	37.7	37.5	37.4	25.4
13:30	39.5	39.3	39.1	24.3
15:00	39.1	38.7	38.7	25.0
16:30	34.0	33.7	33.5	29.6

APPENDIX B

FABRICTAION COST OF SOLAR-CUM-BIOMASS DRYER

Cost of construction for solar-cum-biomass energy hybrid dryer.

Material	Total Requirement	Cost per Unit (Rs)	Total Cost
MS angle bar, 1 inch	80 ft	500/20 ft	2000
MS sheet, 18 gauge	3.5 std. sheets	1500/sheet	5250
MS sheet, 16 gauge	0.5 std. sheet	2000/sheet	1000
Polycarbonate sheet	13 ft × 3 ft	365/ft length	4745
Aluminium sheet	1 std. sheet	2500/sheet	2500
Exhaust fan	1 Nos	1000/piece	1000
Wheels	4 Nos	700/piece	2800
Other materials			2500
Labour cost	8 days	700/day	5600
Total Cost of Dryer			**Rs. 27,395**