INFLUENCE OF THERMAL ENERGY STORAGE IN FORCED CONVECTION INDIRECT SOLAR DRYER DURING DRYING FOOD PRODUCTS

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MECHANICAL ENGINEERING

By

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TO

MY PARENTS

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CERTIFICATE

This is to certify that the thesis entitled "**Influence of thermal energy storage in forced convection indirect solar dryer during drying food products"** being submitted by **Mr. Mugi Vishnu Vardhan Reddy (Roll No: 718133)** for the award of the degree of **Doctor of Philosophy (Ph.D.) in Mechanical Engineering** to the National Institute of Technology, Warangal, India, is a record of the bonafide research work carried out by him under my supervision. The thesis has fulfilled the requirements according to the regulations of this Institute and in my opinion has reached the standards for submission. The results embodied in the thesis have not been submitted to any other University or Institute for the award of any degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled "**Influence of thermal energy storage in forced convection indirect solar dryer during drying food products"** is a bonafide work done by me under the supervision of Dr. Chandramohan V.P. (Professor, MED) and was not submitted elsewhere for award of any degree.

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Abstract

Drying is a preservation method where the moisture is removed from food products for the longer shelf-life and avoiding the attack of microorganisms. Solar drying is inexpensive, renewable in nature and environment friendly compared to other drying methods such as fluidized bed, freeze, infrared radiation, microwave and spray drying. Traditionally, the fruits and vegetables are dried under the open sun called open sun drying (OSD). It has some limitations such as contamination of food by insects and dust, degradation of natural food color and higher drying time. To overcome the limitations of OSD, different solar dryers have been developed. The indirect solar dryer (ISD) is a viable option because it has low manufacturing and operation cost, better control over drying and produces better quality products than other solar dryers. In the ISD, the air is heated in a solar air collector (SAC), flows through the food products which were kept on the trays.

The forced convection ISD (FCISD) increases the drying rate and decreases the drying time than natural convection ISD (NCISD). The performance of FCISD can be enhanced further by integrating a thermal energy storage (TES) system into them. TES materials store excess energy during day time and deliver it at night so that food products can be dried round the clock. The paraffin wax is the most commonly used TES material due to its excellent thermo-physical properties. The TES kept in the drying chamber of ISD gives better dryer performance than other places such as under the SAC and in a separate heat exchanger. The drying kinetics are helpful for researchers to understand the drying behavior and determine the drying time of food products. Energy and exergy analysis (EEA) of the dryer is helpful for better assessment of the performance of ISD as it considers the quality and quantity of energy, losses due to irreversibility and surrounding environmental conditions.

In the present study, the drying experiments were conducted on NCISD and FCISD for two days from morning 8.00 am to evening 5.00 pm. The sample objects considered were guava, muskmelon and beetroot. A trapezoidal duct consist of 3 DC fans powered by solar PV panels is attached at the entrance of the SAC in NCISD to provide FCISD. The TES device consist of 50 number of TES cells that was installed in the drying chamber. Next, the drying experiments were conducted on FCISD without TES device (model-1) and with TES device (model-2) for guava, muskmelon, beetroot and green chilli. In model-2, the experiments were conducted for one day from morning 8.00 am to midnight 12.00 am. During experimentation, mass of the samples, solar radiation, temperature, relative humidity and velocity of air were measured. The

drying kinetics such as moisture content (MC), drying rate (DR), moisture ratio (MR), effective diffusion coefficient (D_{ef}), mass and heat transfer coefficients (h_{mt} and h_{ht}) and activation energy (E_{ac}) were evaluated during drying food products. The drying models from literature which represent MR vs time were evaluated for food products and the best model to describe the experimental data of food products was found. In the energy analysis, collector efficiency ($\eta_{en,SAC}$), drying efficiency ($\eta_{en,dry}$), specific energy consumption (SEC) and specific moisture extraction rate (SMER) were evaluated. In the exergy analysis, exergy input, output, loss and efficiency of the SAC and drying chamber were found. The exergy sustainability indicators such as improvement potential (IP), environmental impact factor (EIF), waste exergy ratio (WER) and sustainability index (SI) were determined.

The initial MC of guava, muskmelon and beetroot were determined to be 5.5355, 12.4156, 7.7535 and 8.3985 kg/kg of dry basis (db), respectively. In NCISD and FCISD, the final MC of guava, muskmelon and beetroot were found to be 0.0244, 0.1605 and 0.0569 db, respectively. The drying duration of 4, 3 and 3 h were reduced during drying guava, muskmelon and beetroot, respectively, in FCISD. The average DR was improved by 28.54, 20.01 and 19.99% during drying guava, muskmelon and beetroot in FCISD, respectively. Two-term exponential model was found to be the best model to describe experimental data of guava in NCISD during drying guava, muskmelon and beetroot. Whereas Page model, Two-term exponential and Two-term exponential models were found to be best models in FCISD during drying guava, muskmelon and beetroot, respectively.

The average D_{ef}, h_{mt} and h_{ht} were improved by 20.3 to 55.59% during drying guava, muskmelon and beetroot in FCISD compared to NCISD. The E_{ac} of guava, muskmelon and beetroot was found to be 136.98 & 116.49 kJ/mol, 38.06 & 28.61 kJ/mol, 27.57 & 23.22 kJ/mol, in NCISD and FCISD, respectively. The $\eta_{en,SAC}$ was increased by 8.34 to 16.63% in FCISD compared to NCISD. Similarly, the $\eta_{en,dry}$ was improved by 19.18− 33.07%. The SEC values were lower and SMER values were higher in FCISD compared to NCISD because lower amount of energy is needed to remove MC in FCISD due to enhanced mass flow rate of air. The average collector outlet temperature (T_{co}) and exergy efficiency of SAC ($\eta_{ex,SAC}$) were found to be lower in FCISD compared to NCISD. The exergy efficiency of drying chamber ($\eta_{ex,dc}$) was enhanced by 11.99, 21.5 and 11.11% during drying guava, muskmelon and beetroot in FCISD. The average IP, WER and EIF were decreased and SI was increased in FCISD compared to NCISD due to lower exergy losses in FCISD.

The model-2 used 9 sunshine hours and 7 non-sunshine hours (total 16 hours) to reach final MC for all samples. The model-1 used 14 sunshine hours for guava drying and 15 sunshine hours for muskmelon, beetroot and chilli drying. The final MC reached in model-2 were 0.0342, 0.2108, 0.0767 and 0.1513 db, during drying guava, muskmelon, beetroot and green chilli, respectively. The drying chamber temperature (T_{dc}) was maintained to be 2.5 to 8.5 °C higher than atmospheric temperature from 6.00 pm to midnight during drying guava, muskmelon, beetroot and chilli in model-2. The average DR was improved by 45.53, 54.04, 41.65, 38.71% during drying guava, muskmelon, beetroot and chilli, respectively, in model-2 compared to model-1.

Minimal improvements in D_{ef}, h_{mt} and h_{ht} were noticed in model-2 compared to model-1 since these were strong function of air velocity. The E_{ac} was decreased by 5.25 to 26.74% in model-2 compared to model-1. The quality of samples dried in both models was found to be the same but better than the samples dried in OSD. The average $\eta_{en,dry}$ was improved by 44.32−48.90% in model-2 compared to model-1 during drying guava, muskmelon, beetroot and green chilli. Similarly, the $\eta_{ex,dc}$ was improved by 4.09−11.74% in model-2 for the same, respectively. The SEC was decreased by 38.57−43.73% and SMER was increased by 62.81−77.65% in model-2 compared to model-1. In model-2, the IP, EIF, WER were decreased by 80.25−85.40%, 33.72−39.66% and 4.65−13.64%, respectively. Whereas, for the same samples, the SI was increased by 2.07−52.99% in model-2 compared to model-1.

The drying kinetics and EEA of NCISD and FCISD revealed that the performance of FCISD was improved compared to NCISD since DC fans powered PV panels were attached in FCISD. Also, FCISD with TES device performed well in all evaluated parameters compared to without TES device by completing the drying in one day using lower amount of solar energy. Uncertainty analysis was performed on all measured and calculated parameters for authenticity of the results.

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Nomenclature

Abbreviations

CPU	Central processing unit
db	dry basis
DR	Drying rate, (kg/h)
DSD	Direct solar dryer
EEA	energy and exergy analysis
EIF	Environmental impact factor
EPBP	Energy payback period
EUR	Energy utilization ratio
FCISD	Forced convection ISD
GI	Galvanized iron
HSD	hybrid solar dryer
IP	Improvement potential, (W)
ISD	Indirect solar dryer
LHS	Latent heat storage
MC	Moisture content
MR	Moisture ratio
MSD	Mixed mode solar dryer
NCISD	Natural convection ISD
OSD	Open sun drying
PCM	Phase change material
PVT	Photovoltaic thermal
RMSE	Root mean square error
SAC	Solar air collector
SEC	Specific energy consumption, (kWh/kg)
SHS	sensible heat storage
SI	sustainability index

SMER	specific moisture extraction rate, (kg/kWh)
TES	thermal energy storage
wb	wet basis
WER	Waste exergy ratio
3E	energy, exergy and economic
4E	energy, exergy, economic and environmental

Symbols

A	Area, (m^2)
B	Thickness of the food product, (m)
c_{pa}	Specific heat of air, (J/kgK)
D_{AB}	Diffusivity value of air in water, (m^2/s)
D_{ef}	Effective diffusion coefficient, (m^2/s)
D_{pf}	Constant for pre-exponential factor
$\dot{E}$	Energy (W)
E_{ac}	Activation energy, (kJ/mol)
$\dot{Ex}$	Exergy, (W)
F	Number of constants
g	Acceleration due to gravity, (m/s)
h	Enthalpy, (J/kg)
h_{ht}	Heat transfer coefficient, (W/m^2K)
h_{mt}	Mass transfer coefficient, (m/s)
I_s	Instantaneous solar radiation, (W/m^2)
k	Thermal conductivity, (W/mK)
L	Latent heat of vaporization, (J/kg)
Le	Lewis number
m	Mass, (kg)
$\dot{m}$	Mass flow rate, (kg/s)
N	Number of experiments

$\dot{Q}$	Heat transfer rate (W)
R	dependent parameter
R_u	Universal gas constant
R^2	Coefficient of determination
s	entropy, (J/kgK)
T	Temperature, (°C)
u	Internal energy, (J)
v	Velocity, (m/s)
V	Volume of the food product, (m^3)
$\dot{W}$	Work done, (W)
w	uncertainty of dependent parameter
$w_1, w_2 \ldots w_n$	uncertainty values for independent parameters
$x_1, x_2 \ldots x_n$	independent parameters
z	Height from the datum, (m)

Greek symbols

η	efficiency, (%)
χ^2	reduced chi-square
α	thermal diffusivity, (m^2/s)
μ	chemical potential, (kJ/mol)
τ	transmissivity
∞	reference

Subscripts

a	air
abs	absorber plate
amp, 0	atmosphere
ch	chemical
ci	collector inlet
co	collector outlet

da	drying air
dc	drying chamber
dry	dryer
en	energy
ex	exergy
exp	experimental
i	initial, inlet
in	input
ls	loss
o	outlet
out	output
pre	predicted
pw	paraffin wax
s	surface
sn	sun
tr1, tr2, tr3, tr4	Trays−1, 2, 3 and 4
u	useful
w	water

Chapter 1

Introduction

Chapter 1

1. Introduction

To maintain harmony between the growing world population and food supply, food wastage must be controlled and minimized at the time of harvesting, processing, marketing and distribution. The quality, taste, colour and flavour of food materials degrade because of inadequate storage units (cold storage) and lack of processing techniques. Many developing countries experience significant losses in agricultural food products. It is calculated that the total post-harvesting losses in fruits and vegetables are 30 to 40% of the total production [1] and this is one of the main reasons for the increase in food prices. Preservation of agricultural products is important to keep them in safe condition for a long time without deterioration of quality. Drying is a popular technique to preserve agricultural products by removing the moisture content (MC) from the product. The different drying methods were used to dry agricultural products such as solar drying, convective drying, freeze drying, fluidized bed drying, microwave drying etc.

The solar energy is abundantly available in nature and it can be used for drying of food products for economic and environmental benefits over other available energies [2]. This chapter gives an overview to various solar dryers, thermal energy storage (TES) materials, energy and exergy analysis (EEA) and different food products used in the present study. The motivation for the present study, aim and objectives of the present study are discussed. The work plan and organisation of the thesis were mentioned.

1.1. Solar drying

Traditionally, food products are dried under open sun called open sun drying (OSD). The OSD method has lot of disadvantages such as higher drying period, low quality products due to contamination of dirt, and higher amount of loss of products by animals, birds and microorganisms [3]. Solar dryers can overcome the limitations of OSD. The solar dryers are divided into two main types such as natural and forced convection solar dryers (**Fig. 1.1**). In natural convection solar dryers, the air flow is generated by buoyancy forces. In forced convection solar dryers, the air flow is generated by a fan or blower powered by electricity or solar photovoltaic (PV) panels [4]. There are four groups of solar dryers in either natural or forced convection: direct, indirect, mixed-mode and hybrid solar dryers [5].

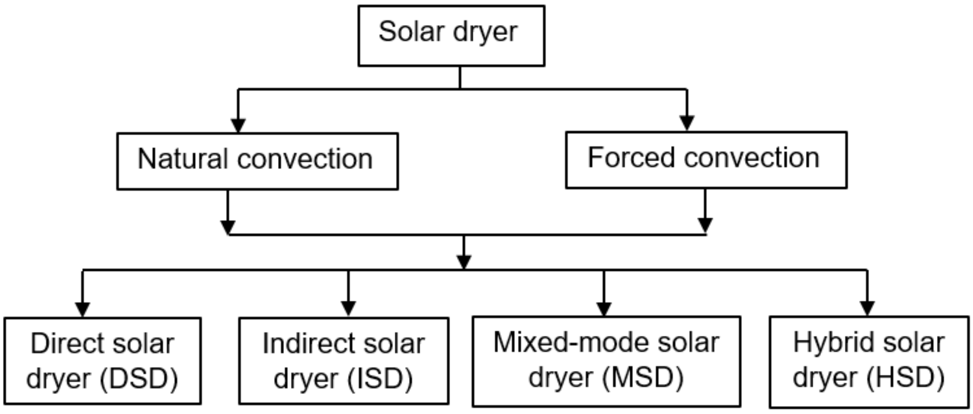


Fig. 1.1. Classification of solar dryers

1.1.1. Direct solar dryer (DSD)

It contains a box or greenhouse covered by transparent cover under which the products are placed on a tray (**Fig. 1.2**). Solar energy is transmitted through a transparent glass and reaches the products directly [6]. It produces high temperatures because of low convection losses. It has advantages of protection from dust and animals. But it has disadvantages of producing lower quality of products since they are directly exposed to the sun.

(a) (b)

Fig. 1.2. Pictorial view of (a) box type [7] and (b) greenhouse type [8] direct solar dryer

1.1.2. Indirect solar dryer (ISD)

It has a solar air collector (SAC) where the air is heated. SAC is fixed with a drying chamber where the products are placed on trays. A chimney is on the top for moisture transfer. In the ISD, the hot air exited from SAC flows over the trays inside the drying chamber and absorbs moisture from the food products [9]. The ISDs are divided into two types such as natural convection ISD (**Fig. 1.3)** and forced convection ISD. ISD overcomes the disadvantages of OSD and DSD and produces better quality food products since food products are not directly exposed to sun.

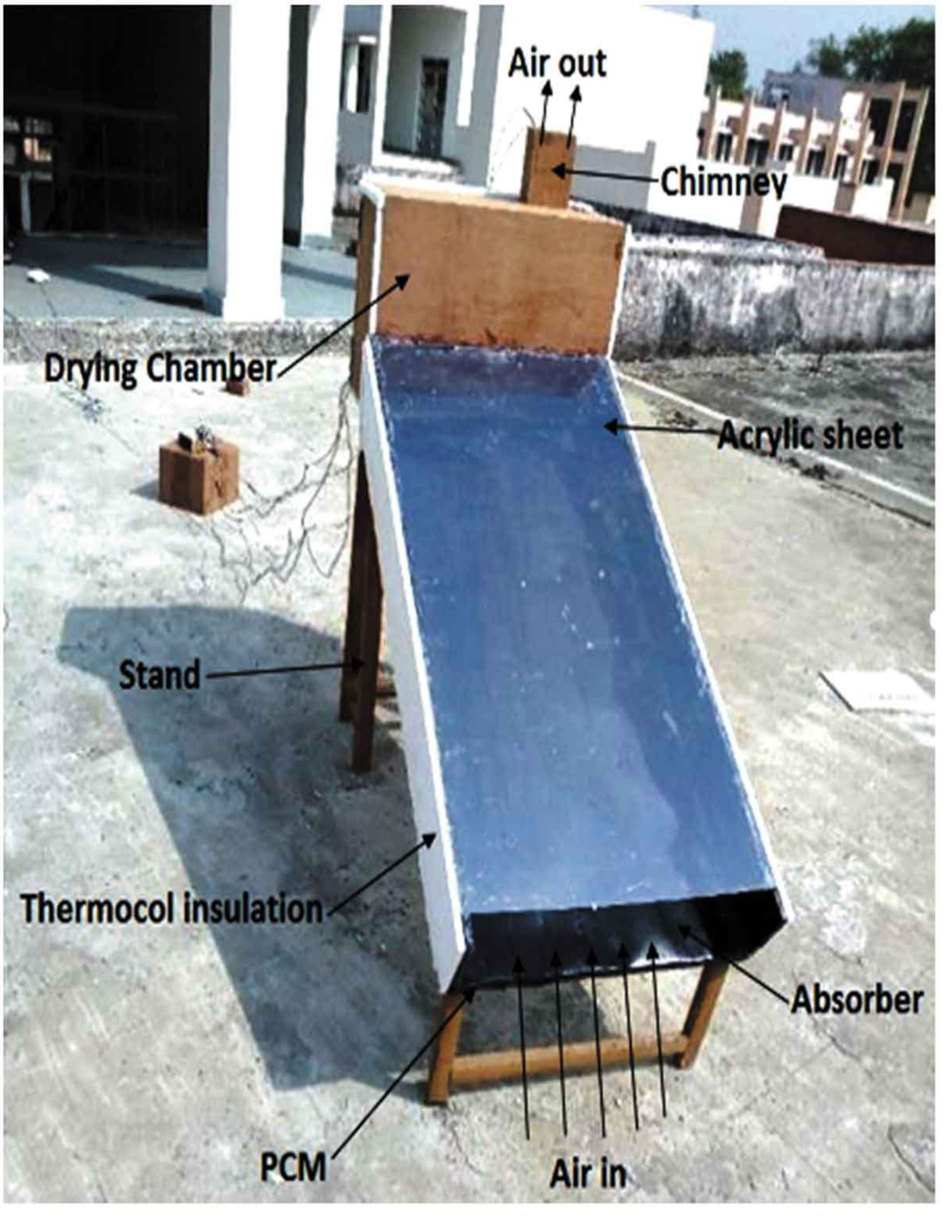


Fig. 1.3. Experimental setup of natural convection indirect solar dryer [10]

1.1.3. Mixed mode solar dryer (MSD)

It is a combined model of DSD and ISD dryers. It consists of SAC, a drying chamber with transparent covers and a chimney. Fig. 1.4 represents the schematic diagram of MSD with two SACs. The moisture in the food products is made to evaporate due to heated air from SAC and direct solar radiation [11]. It has advantages of getting high temperatures than ISD but it produces lower quality food products since food products are exposed to sun.

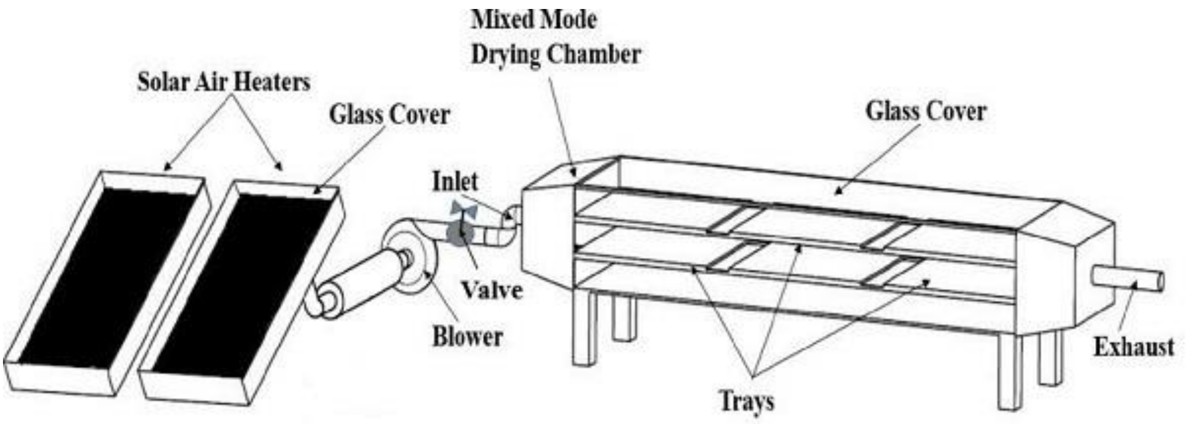


Fig. 1.4. Schematic diagram of mixed mode solar dryer [12]

1.1.4. Hybrid solar dryer (HSD)

In HSD dryers, the moisture in the food products is evaporated by not only solar energy but through other auxiliary energy sources such as biomass, electricity, waste heat, etc [4]. Fig. 1.5. shows the schematic diagram of HSD integrated with electric heater. The HSD produces high temperatures but design of HSD is complicated and have high operating and maintenance cost.

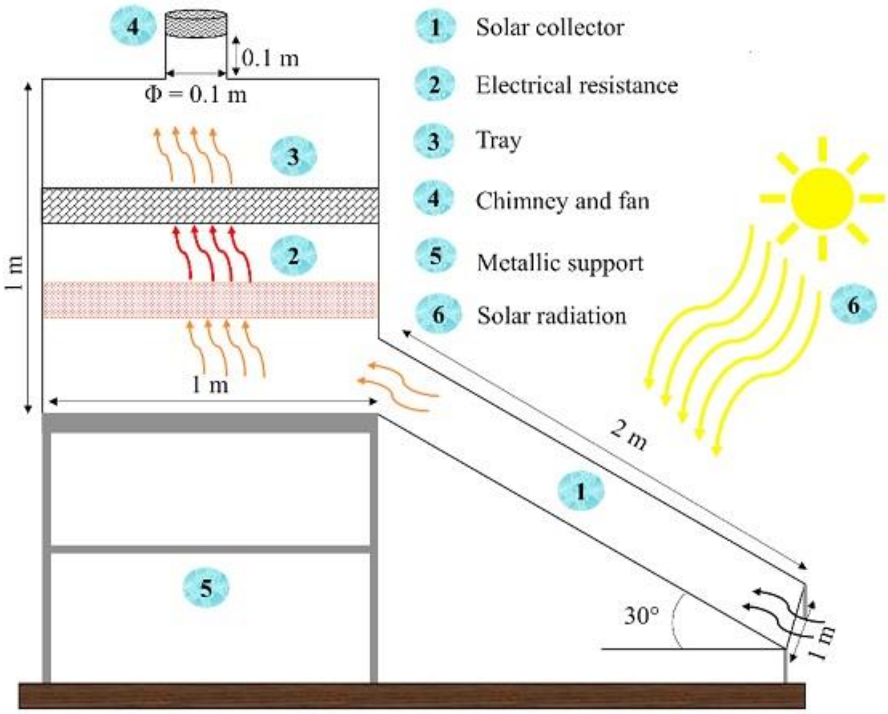


Fig. 1.5. Schematic diagram of hybrid solar dryer [13]

1.1.5. Thermal energy storage materials

The solar drying process is totally depending on sun. The solar radiation varies with time and it depends on geographic location and environment. The drying cannot be continued after the sunset or in cloudy days. The integration of TES materials enables drying continued after the sunset and maintain uniform temperature in the drying chamber. TES is divided into three types such as sensible heat storage (SHS), latent heat storage (LHS) and thermochemical storage [14]. In the SHS, the thermal energy is stored by specific heat and change in temperature of liquid or fluid. In the LHS, the thermal energy stored by latent heat of fusion or vaporization by change in phase from solid to liquid or liquid to vapor, respectively. In the thermochemical storage, the energy is stored or released by breaking or combination of molecular bonds. Out of three types, LHS materials are advantageous since they have high storage capacity and melt and solidify at a constant temperature. Phase change material (PCM) such as paraffin wax has been widely used as LHS material in solar dryers due to high thermal and chemical stability, high storage density, compatibility with materials, high nucleation rate and lower degradation after a number of cycles [15]. Hence, TES materials are integrated with solar dryers to continue the drying during off-sunshine hours.

1.1.6. Energy and exergy analysis (EEA)

Energy and exergy analysis (EEA) is an essential mechanism to describe the effectiveness of drying process in the dryer. Energy analysis of solar dryer describes the thermal performance of the solar dryer based on the first law of thermodynamics. It gives the information about the type of energies and quantities of energy input and output of a process. The energy analysis does not consider the quality of energy, losses due to irreversibility and surrounding environment conditions [16]. Exergy analysis overcomes the above limitations and it gives a clear idea about the improvement of the system. Exergy is defined as maximum work that can be obtained from a system. There will be always exergy losses due to irreversibility in a process, which is equal to entropy generation [17]. It is helpful for the solar dryer to optimize the drying conditions, estimate irreversibility and find the deviation of the actual process from the ideal process. EEA is useful for better evaluation of thermodynamic performance of system, designing efficient solar thermal systems and optimizing the drying operation as it gives quality of energy, magnitudes of losses and the effect of surrounding parameters. Therefore, in the present study EEA was carried out during drying food products.

1.2. The overview of some fruits and vegetables

The various food products including fruits and vegetables were cultivated by farmers in India and all over the globe. The MC in the food products makes them perishable after some time. So, the food products can be dried and used as snacks, powders, pigments and nutritional supplement. In the present study, guava, muskmelon, beetroot and green chilli are selected based on their production, nutritional and health benefits and shown in **Fig. 1.6.**

(a) (b) (c) (d)

Fig. 1.6. Snapshot of (a) guava, (b) muskmelon, (c) beetroot and (d) green chilli

1.2.1. Guava

Guava (Psidium guajava) is one of the tropical and subtropical fruits that consists of higher amounts of vitamin C than any other citrus fruit and it is crucial for a higher immune system. It has a high MC – close to 85% which makes it perishable so storage and transportation difficulty arises. Guava also has substantial amounts of calcium, iron, phosphorous, vitamin A and B and high fibre content which increases the digestive capacity [18]. It is used to treat cancer and diseases like thyroid, scurvy and hepatic diseases, benefit for improvement in eye sight and brain.

1.2.2. Muskmelon

Muskmelon (Cucumis melo) belongs to the Cucurbitaceae family with a yellow-orange coloured soft flesh with nice flavour, taste and texture. It is a tropical fruit that contains great quantum of vitamin A, vitamin C, β-carotene, potassium, folic acid and dietary fibre [19]. It has also low saturated fat and cholesterol, pigments and minerals which provides numerous nutritional and health benefits. It has lower shelf life due to its high MC (almost 90%). The drying of muskmelon prevents the deterioration of its flavour and quality. Drying also prevents the spoilage effect of muskmelon by micro-organisms.

1.2.3. Beetroot

The beetroot (Beta Vulgaris L.) belongs to Chenopodiaceae family that is popular and traditional vegetable throughout the globe. It has MC around 85%. Beetroots contain a variety of active compounds, including betalains, flavonoids, carotenoids, polyphenols, and saponins. Beetroot has received a lot of attention as a health-promoting vegetable in the past few decades because of its anti-carcinogenic, anti-hypertensive, anti-inflammatory and antioxidant properties [20]. Dried beetroot's colour and flavour are considered the most significant attributes influencing the consumers' acceptability. In the food industry, the dried beetroot could be used in components of the soup, nutritional supplement to athletes and natural pigment. From the dried beetroot slabs, the beetroot powder is made and it is one of colouring agents for a lot of cooked food items, ice-creams, cakes, sweets, etc. [21].

1.2.4. Green chilli

Green chilli (Capsicum Annum) which originated in Mexico belongs to Solanaceae family. India is the biggest consumer and producer of chillies on the globe. The major chilli producing states in India are Telangana, Andhra Pradesh, Karnataka, Madhya Pradesh and Orissa. Since green chillies are used in cooking and consumed daily, it is cultivated by farmers round the year. Fresh chilli has high amounts of vitamin C and vitamin A. Fresh chillies have seasonal variation in terms of cost, high wastage, huge MC and limited shelf life. Chilli has numerous health benefits because it has anti-inflammatory, anti-neoplastic, anti-fungal, anti-cancer and anti-arthritic properties [22].

1.2.5. Critical properties of food products

The critical properties of the food products to be controlled in the dryer are shrinkage, texture, colour and retention of nutrients.

1.2.5.1. Shrinkage

During the solar drying process of food products, the heated air removes the water from the food product which establishes a pressure difference between the inner surface of the product and the external environmental pressure. This produces contracting stresses in the food tissues results in shrinkage of the material [23]. It creates a change in shape and sometimes generates cracks in the product. It is observed the shrinkage of muskmelon slices is higher than other food products since muskmelon slices have soft and hydrophilic surfaces and it can be controlled by slow drying of muskmelon slices.

1.2.5.2. Texture

Texture attributes such as cohesiveness, resilience. hardness, chewiness, springiness and gumminess can be determined by texture profile analyses. The drying rate and drying air temperature have a significant impact on the texture of the food product. Generally, more textural changes are about through higher temperatures and drying rates [24]. According to the rate of water removed, the structural changes that occur during drying affect the texture of the finished product. The cubic structure of dried muskmelon slice has collapsed with different angles and large volume reduction is observed than other food products. During solar drying of guava, beetroot and chilli, the dense structure is formed and the dried product becomes harder. The texture of the food products can be controlled by maintaining low temperature in the drying chamber in the ISD.

1.2.5.3. Colour

Colour of food products changed due to chemical reactions and degradation of pigments. The longer drying duration and higher drying air temperature result in great losses in colour [25]. Any one of these three mechanisms could cause the colour change in food products.

i. Residual enzymatic browning: the residual enzymes found in food products like polyphenol oxidases, promote oxidation and colour change.

ii. Maillard's reaction: the reaction between reducing sugars of carbohydrates and amino group of proteins in the presence of heat causes change in colour of the food products.

iii. Carmelization: the transformation of sugars into dark colored while heating the food products.

It is observed that color degradation is lower for food products dried in ISD compared to OSD [26]. The colour of all the selected products would be degraded in the ISD and it can be controlled by maintaining the temperature that does not promote chemical reactions.

1.2.5.4. Retention of nutrients

Drying can change the value of different nutrients in food products. Every food product contains important nutrients that shouldn't be significantly lost during drying. It is observed from the literature that vitamin C, total phenolic content and antioxidant activity were assessed in guava slices [27], vitamin C, total soluble solids, potassium and amino acids were assessed in muskmelon slices [28], total phenolic content and antioxidant activity were determined in beetroot slices [21] and vitamin C, total phenolic content and antioxidant activity were assessed in chilli samples [29]. The total phenolic content and vitamin C were decreased and antioxidant activity was increased as temperature was decreased [29]. So, depend on the type of nutrients need to be retained in the dried product the temperature of the dryer has to be controlled.

The guava, muskmelon, beetroot and green chilli were not extensively studied in the literature during drying in ISD and the properties of dried samples such as shrinkage, texture, colour and retention of nutrients were found to be better in ISD compared to OSD. The guava has substantial amounts of vitamin A, B and C, calcium, iron, phosphorous and fibre content. The muskmelon contains vitamin A and C, β-carotene, potassium and folic acid. The beetroot has betalains, flavonoids, carotenoids, polyphenols, and saponins. The chilli contains vitamin C, capsaicinoids and phenolic compounds. Hence these food products were chosen in the present study.

1.3. Motivation

The ISD is advantageous than other dryers as it produces quality food products within lower duration by providing better retention of color, desired temperature and lower damage to food products. It also has low operating cost and better control over drying. The forced convection ISD (FCISD) increases the drying rate and decreases drying time than natural convection ISD (NCISD). The performance of ISD can be enhanced further by integrating TES systems into them. TES materials store excess energy during day time and deliver it at night so that food products can be dried round the clock. ISD with TES systems help to enhance the performance of the ISD, reduce drying time, minimize manpower needed and increase the overall drying efficiency of the system [30]. The energy analysis alone provides limited data on the type of energy used and the amount of energy utilized during a drying process. The energy and exergy analysis of ISD provides the data on energy and exergy input, output, losses and efficiencies for solar air collector and drying chamber. The exergy analysis provides irreversibility in a process and gives an understanding of how much the real process deviates from the ideal process [31]. EEA of the dryer is helpful for better assessment of the performance of ISD, design the effective dryer and optimize the drying process as it considers the quality and quantity of energy, losses due to irreversibility and surrounding environmental conditions.

In the present study, the TES device is developed and installed in the drying chamber. The FCISD is developed from NCISD and drying kinetics of guava, muskmelon and beetroot, and EEA of NCISD and FCISD are evaluated. Next, the drying kinetics of guava, muskmelon, beetroot and green chilli, and EEA of FCISD without and with TES are evaluated.

1.4. Aim and Objectives

Aim: To develop an FCISD with TES device and evaluation of drying kinetics and energy and exergy analysis

The major objectives of the present study are

1. To develop a thermal energy storage (TES) device in the drying chamber of indirect solar dryer (ISD).

2. To evaluate the influence of forced convection ISD (FCISD) on drying kinetics of guava, muskmelon and beetroot slices using DC fans operated with solar PV panels without TES device.
3. To identify the impact of FCISD on energy and exergy analysis of ISD without TES device during drying guava, muskmelon and beetroot slices.
4. To find the effect of TES device on drying kinetics of guava, muskmelon, beetroot and green chilli in FCISD.
5. To analyse the effect of TES device on energy and exergy analysis of FCISD during drying guava, muskmelon, beetroot and green chilli.

1.5. Work plan

The TES device is developed in the drying chamber of ISD. The drying kinetics of guava, muskmelon and beetroot were analysed in NCISD and FCISD dryers. The EEA analysis of NCISD and FCISD dryers during drying guava, muskmelon and beetroot were carried out. The comparative study was conducted for all parameters in NCISD and FCISD dryers. Next, the drying kinetics of guava, muskmelon, beetroot and green chilli and EAA of FCISD without and with TES device were analysed and compared. The objectives of the present work are conducted in a step-by-step process as shown in the flow chart (**Fig. 1.7**)

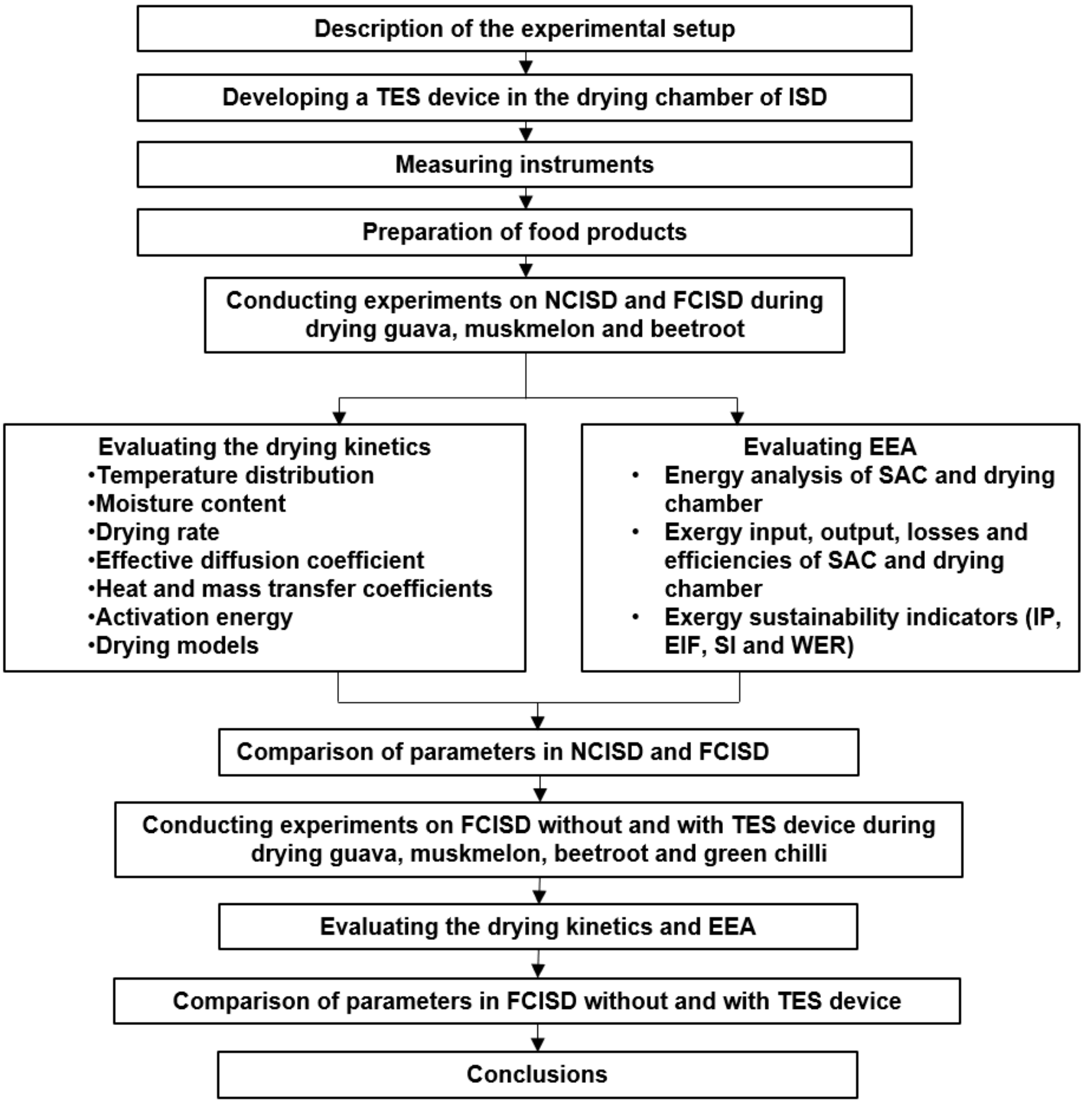


Fig. 1.7. Flow chart of showing the work plan

1.6. Organization of the thesis

The thesis is organized as follows:

The **first chapter** consists of introduction, motivation and objectives of the work. Different type of solar dryers such as direct, indirect, mixed mode and hybrid solar dryers are explained. Overview of TES materials, EEA and some fruits and vegetables are explained. The motivation for the present study, aim and objectives of the work are given. The work plan and organisation of the thesis are mentioned.

The **second chapter** discusses literature review on various solar dryers during different food products. This chapter discussed the literature review on drying kinetics and EEA of solar dryers such as DSD, MSD, HSD and ISD without and with TES are discussed. The literature review on different food products used in the present is discussed. Based on literature review, literature gaps are mentioned. The specific objectives of each major objective are mentioned.

The **third chapter** discusses methodology of experimental work. The working principle of ISD and components of NCISD and FCISD dryers are explained. The components of FCISD setup with TES are explained. The measuring instruments used in the experimentation are explained. Procedures for conducting experiments are discussed. The initial moisture content of the food products used in the present study are discussed. The equations used to evaluate the drying kinetics and EEA of dryers were explained.

The **fourth chapter** is related to results and discussion on NCISD and FCISD dryers without TES device during drying guava, muskmelon and beetroot. The temperature distribution at different locations of the dryer is evaluated in NCISD and FCISD dryers. The drying kinetics such as moisture content, drying rate, moisture ratio, effective diffusion coefficient, heat and mass transfer coefficients, and activation energy are evaluated in NCISD and FCISD dryers. The drying models are evaluated using coefficient of determination and reduced-chi square, and best model to describe the drying data of food products is estimated in NCISD and FCISD. The energy and exergy analysis of SAC and drying chamber in NCISD and FCISD dryers is conducted. The exergy sustainability indicators such as IP, EIF, SI and WER are examined in NCISD and FCISD dryers. The comparative analysis was conducted in NCISD and FCISD dryers during drying food products. Next, the results are discussed on FCISD without (model-1) and with TES device (model-2) during drying guava, muskmelon, beetroot and green chilli. The temperature distribution at different locations of the dryer is estimated in model-1 and model-2. The drying kinetics such as MC, drying rate, moisture ratio, effective diffusion coefficient, heat and mass transfer coefficients, and activation energy in model-1 and model-2. The drying models were evaluated using coefficient of determination and reduced-chi square, and best model to describe the drying data of food products is estimated in model-1 and model-2. The energy and exergy analysis of SAC and drying chamber in model-1 and model-2 is conducted. The exergy sustainability indicators such as IP, EIF, SI and WER are examined in model-1 and model-2. The comparative analysis was conducted in model-1 and model-2 during drying food products.

The **fifth chapter** is related to conclusions from experimental results. The conclusions drawn from drying kinetics and EEA of NCISD and FCISD without TES device during drying guava, muskmelon and beetroot are presented. The conclusions from drying kinetics and EEA of FCISD without and with TES device during drying guava, muskmelon, beetroot and green chilli are presented. At the end, the overall conclusions and future scope of the work are included.

Chapter 2

Literature review

Chapter 2

2. Literature review

2.1. Introduction

Drying is one of the preservation methods of food products. It is a simultaneous heat and mass transfer process. The different methods used for drying food products are solar, convective, microwave, infrared, freeze and fluidized bed drying. Food drying through solar energy has a lot of advantages over other drying methods because of renewable in nature, abundant and freely available. Conventionally, the food products are dried in open air called open sun drying (OSD). The disadvantages of the OSD method are contamination of dust, colour and flavour changes and disturbances from animals and insects. Different solar dryers are invented to overcome the above disadvantages of the OSD method. The researchers developed different types of solar dryers to dry different agricultural food products. The drying kinetics of food products helpful to evaluate the drying behavior and drying period of food products. The different TES materials were used at various locations in the solar dryers to continue drying after the sunset. This chapter covers some of the works carried out on drying kinetics of food products in various solar dryers and EEA of various solar dryers integrated without and with TES materials. The various studies performed on selected food products in dryers are also discussed. At last, the conclusions from literature review, literature gaps and specific objectives of the work are mentioned.

2.2. Studies on drying kinetics and EEA of solar dryers without TES

In this section, the drying kinetics of various food products in different solar dryers such as DSD, MSD, HSD and ISD without storage are explained. The studies on energy and exergy analysis of various solar dryers without storage were also explained.

2.2.1. Direct solar dryer (DSD)

Dissa et al. [32] developed a DSD consisting of four trays to dry the Brooks and Amelie mangoes. The drying kinetics were compared using 10 mathematical models from the literature. The Approximation of diffusion and Two-term models were the fitting models to describe the drying curve of mangoes. The effective diffusion coefficient (D_{ef}) was 8.80×10^{-11} and 12.57×10^{-11} m^2/s for Brooks and Amelie mangoes, respectively.

Mani and Natesan [33] constructed forced DSD for drying green peas. The coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were employed to pick the best drying relations. Midilli and Kucuck model was the finest to predict drying characters of green peas. A drying period of 37.5% was saved in DSD against OSD. Higher energy content in dried peas was observed in DSD than OSD method.

Tiwari et al. [34] conducted EEA on the DSD during the drying of fish under natural and forced dryers. Numerical models were generated to find the amount of water evaporated, the temperatures of drying air and on the surface of fish and the results were validated with various experiments. The energy efficiency of the dryer ($\eta_{en,dry}$) ranged from 0.01 to 5.71% and 0.01 to 6.01% in natural and forced dryers, respectively.

Mishra et al. [35] conducted an energy, exergy, economic and environmental (4E) analysis of DSD in natural and forced modes under no-load conditions. The energy payback period (EPBP) of DSD was 1.5 and 1.1 years for active and passive mode, respectively. The exergy efficiency of drying chamber ($\eta_{ex,dc}$) was observed to be 4.1 and 4.5%, under forced and natural modes, respectively.

2.2.2. Mixed mode solar dryer (MSD)

Ekka et al. [12] constructed a MSD which consisted of two SACs, a drying chamber and a fan to dry the cluster figs. At an optimum 0.062 kg/s, specific moisture extraction rate (SMER) and $\eta_{en,dry}$ of MSD were found to be 0.616 kg/kWh and 40.9%, respectively. The Wang and Singh model gave better agreement with their experimental solution.

Cesar et al. [36] evaluated the drying characteristics of tomato pieces in natural convection MSD dryer and concluded that the modified Henderson and Pabis model was the best-fitted model. The average $\eta_{en,dry}$ and collector efficiency ($\eta_{en,SAC}$) of MSD dryer were observed to be 3.58% and 55.45%, respectively.

Karthikeyan and Murugavelh [37] carried drying experiments on a forced convection MSD while drying turmeric. The temperature of the air in the drying chamber (T_{dc}) was maintained from 42.2 to 82.8 ºC. EEA analysis has been carried out and energy utilisation ratio (EUR) values were found and these were in the range of 9.75 - 33.98%. The $\eta_{ex,dc}$ was ranged from 23.25 to 73.31% with an average of 49.12%.

2.2.3. Hybrid solar dryer (HSD)

Wang et al. [38] developed a HSD consists of SAC, fan, auxiliary heating system, automatic temperature controller and drying chamber. The fan was run by electricity and was used to control the volume of air which regulated the air temperature in the chamber. The SMER was found to be 1.67 kg/kWh at a temperature of 52 ºC. D_{ef} values of mango slices ranged from 6.41×10^{-11} to 1.18×10^{-10} m^2/s for the temperature range of 40 and 52 °C. The Page model was found to be the best model for mango slices.

Amjad et al. [39] built a HSD comprised of a solar evacuated tube collector and a gas burner. They studied the EEA analysis during the drying of green chilli. The EUR and $\eta_{ex,dc}$ were ranged from 16.55 to 56.89% and 33.95 to 74.11%, respectively.

Cifci et al. [40] studied EEA of photovoltaic thermal (PVT) collector ISD during drying mint leaves. It is observed that the $\eta_{en,SAC}$ was ranged from 50.25 to 58.16% and 47.46 to 54.86% of finned and finless PVT collectors, respectively. The mean $\eta_{ex,dc}$ was ranged from 43.04 to 56.11% and 41.85 to 52.01% with finned and finless PVT collectors, respectively. The sustainability index (SI) was found to be in the range of 2.38 to 3.25 and 2.16 to 2.75 for finned and finless PVT collectors, respectively.

2.2.4. Indirect solar dryer (ISD)

Sunil et al. [41] developed an NCISD that had a SAC and a drying chamber with two trays. The fenugreek leaves were dried in the setup. The leaves reached an average final MC of 0.079

from 6.692 kg/kg of dry basis (db) in 6 and 13 h in ISD and OSD, respectively. Wang and Singh model was fitted with drying curves and identified that they were the best models of NCISD and OSD dryers with a good R^2 and lowest value of RMSE, the sum of squares error and mean squared error.

Lingayat et al. [42] fabricated an NCISD for drying brinjal and tomato. The initial MC of brinjal and tomato were 10.111 and 15.667 db and these were reached 0.498 and 0.803 db, respectively. The D_{ef} for brinjal and tomato were 4.00 and 3.6×10^{-9} m^2/s, respectively. Page, Wang and Singh models were fitted the drying curves of brinjal and tomato, respectively.

Nukulwar and Tungikar [43] examined drying models of turmeric in NCISD and OSD, respectively. The turmeric with an initial MC of 3.348 db decreased to 0.219 db in 24 and 40 h, respectively, in NCISD and OSD methods. Page model was estimated to be the perfect fitting model. The quality of dried turmeric in NCISD found to be better than OSD.

Panwar [44] performed EEA in NCISD dryer during the drying of coriander leaves. The air temperature was varied from 36 to 56 °C. The initial MC of coriander leaves was 7.33 db and reduced to a final MC of 0.8181 db in drying time of 7.5 h. Midilli model found to be best to describe the drying kinetics. The $\eta_{en,dry}$ values were in a range of 7.81−37.93%, while $\eta_{ex,dc}$ values were in a range of 55.35−79.39%.

El-Sebaii and Shalaby [45] designed a forced convection double pass ISD and experiments were conducted for mint and thymus. Initial MC of mint and thymus were 9.28 and 10.49 db, respectively. After comparing different models, it was observed that Midilli and Kucuk model was fit for describing drying behaviour of mint and modified Page model was fit for thymus.

Akbulut and Durmus [46] carried out drying experiments in a FCISD for drying mulberry. EEA was conducted at five mass flow rates ranging from 0.014 to 0.036 kg/s. The values of EUR and exergy loss ranged between 0.205−0.552 and 2.65−10.82 W, respectively. They reported that as mass flow rate increased, EUR and exergy loss decreased and exergy efficiency increased. The $\eta_{ex,dc}$ was between 21.3 and 93.3%.

Sethi et al. [47] conducted energy, exergy and economic (3E) analysis of FCISD during the drying of potato slices. The average exergy efficiency of SAC ($\eta_{ex,SAC}$) and $\eta_{ex,dc}$ was 1.99%

and 58.14% with V-corrugated SAC and 2.28% and 56.12% with flat plate SAC, respectively. The payback period of the dryer was noticed to be 0.48 years with V-corrugated SAC.

2.3. Studies on drying kinetics and EEA of solar dryers with TES

In this section, the drying kinetics of various food products in different solar dryers such as DSD, MSD, HSD and ISD with TES are explained. The studies conducted on EAA analysis of various solar dryers with TES were also explained.

2.3.1. Direct solar dryer (DSD)

Ayyappan et al. [48] examined the impact of different sensible heat storage (SHS) substances including rock-bed, sand and concrete in DSD during drying coconuts. The T_{dc} was maintained 12−16 °C and 3−6 °C higher than the atmospheric temperature (T_{amp}) during day and night, respectively. The $\eta_{en,dry}$ was found to be 11.65, 11 and 9.5% with rock-bed, sand and concrete as SHS materials, respectively. The drying time was saved by 69%, 62% and 55% compared to OSD with rock-bed, sand and concrete, respectively.

Gopinath et al. [49] explored the drying of grapes in a DSD with and without TES utilizing paraffin wax as a phase change material (PCM). The PCM was packed inside and below the meshes of the drying chamber. It is noticed that the drying duration for grapes was 52, 34, 22 and 10 h in OSD, solar dryer without a storage unit, with 100 and 200 g of PCM, respectively. They also reported that T_{dc} was maintained above 50 °C for a duration of 4 h.

Nimnuan and Nabnean [50] conducted experiments on DSD with concrete as SHS during drying ginger from 9 db to 0.11 db. The T_{dc} was in the range of 30−55 °C. The quality of ginger slices was found to be better compared to OSD and 67% of the drying period was saved in the DSD.

2.3.2. Mixed mode solar dryer (MSD)

Baniasadi et al. [51] fabricated a MSD integrated with TES system during drying apricot pieces. The PCM chosen was paraffin wax and it was poured inside the copper coil that was located in the bottom tray of the drying section. Apricot slices were dried from an MC of 6.1428 to 0.333 db in 11 h. It was reported that the drying time was reduced by 50% due to TES. The $\eta_{en,dry}$ was found to be 10.91 and 10.58% with and without storage, respectively.

Similarly, Abubaker et al. [52] conducted experiments on MSD with rocks as SHS and without storage during drying yam slices. The $\eta_{\mathrm{en},SAC}$ and $\eta_{en,dry}$ were observed to be 67.30% and 28.20% with storage, and the same were 40.10% and 23.1% without storage, respectively.

Lakshmi et al. [53] performed experiments with black pepper on the MSD with a paraffin wax storage tank and two SACs. The drying time for black pepper to reach final MC in MSD and OSD was 14 and 59 h, respectively. The $\eta_{en,dry}$ was observed to be 51%. The specific energy consumption (SEC) was concluded to be 2.2 kWh/kg.

2.3.3. Hybrid solar dryer (HSD)

Hossain et al. [54] experimentally examined a HSD that contained SAC and a water storage unit with a heat exchanger while drying tomato slices. The auxiliary heating coil was used to warm the water during drying at the night. The tomato slabs were reduced from an initial MC of 27.74 to 0.17 db in a period of 126 h. The $\eta_{\mathrm{en},SAC}$ and $\eta_{en,dry}$ were found to be 35.29% and 22.48%, respectively.

Murali et al. [55] made a HSD that consisted of a solar water heater, an LPG cylinder as the auxiliary source, storage water tank and a drying chamber. The shrimps are dried to a final MC of 0.1818 db from an initial value of 3.2937 db within 6 h. The LPG cylinder supplied 26.07% of the total energy needed. The maximum $\eta_{en,dry}$ and $\eta_{\mathrm{en},SAC}$ were found to be 37.09% and 42.37%, respectively.

Deeto et al. [56] constructed a HSD consisting of a solar greenhouse dryer and water storage tank integrated with SAC for drying coffee beans. The hot water was used after the sunset to dry the coffee beans. The coffee beans were reduced to 0.136 from 1.22 db in a period of 12 h. The drying behaviour of coffee beans could be matched with Midilli et al. model. The value of D_{ef} was found to be 9.754×10^{-11} m^2/s.

2.3.4. Indirect solar dryer (ISD)

Cetina-Quinones et al. [57] conducted drying experiments of tomatoes on an NCISD with two SHS materials such as limestone and beach sand at three possible locations: under the collector, top and bottom of the drying chamber. The $\eta_{en,dry}$ was found to be 12.57 and 11.02% in NCISD with limestone and beach sand, respectively. The drying duration to achieve the final MC of tomato was observed to be 25, 22 and 23 in NCISD without storage, with limestone and with coastal sand, respectively.

Singh and Mall [10] constructed an NCISD for banana chips drying that consisted of paraffin wax as PCM. The PCM setup was located beneath the absorber sheet of the SAC. The chips were dried from an initial MC of 2.73 db to a final MC of 0.25 db in 18 h (13 h in day time and another 5 h after sunset). Out of 14 models, Modified Henderson and Pabis model suited the drying behaviour of banana slices. The average $\eta_{en,dry}$ and $\eta_{\mathrm{en},SAC}$ were found to be 2.98% and 66.32%, respectively.

Jain and Tewari [58] developed an NCISD integrating PCM tubes below and above the trays of the drying chamber. 48 kg of paraffin wax was used as PCM to reserve and release the heat while drying leafy herbs. It is noticed that T_{dc} was maintained to be 6 °C higher than the T_{amp} after the sunset from 5 to 6 h. The $\eta_{en,dry}$ of 28% is observed in the developed setup. The payback period was reported to be 1.57 years.

Kesavan et al. [59] developed an FCISD which consisted of triple-pass SAC with sand as SHS material. The optimum mass flow rate of air was found to be 0.062 kg/s. The final MC achieved was 0.149 from 3.167 db. The $\eta_{\mathrm{en},SAC}$ was in the range of 12−66% with an average of 45%. The $\eta_{ex,dc}$ was varied between 2.8 to 87.02% with an average of 53.57%.

Shringi et al. [60] developed an FCISD with PCM as TES during drying of garlic cloves. It consisted of an evacuated heat pipe collector, heat storage unit and drying chamber. When the recirculation of air in the drying chamber was considered, the $\eta_{en,dry}$ was in the range of 3.98−14.95%, while $\eta_{ex,dc}$ was in the range of 67.06−88.24%.

Nabnean et al. [61] constructed an FCISD integrated with a heat exchanger between the water storage tank and drying chamber. The warmed water from SAC was filled in a tank and was utilized to heat the air via a heat exchanger. The sample object considered was tomato slabs. The ranges of $\eta_{\mathrm{en},SAC}$ and T_{dc} were 21 to 69% and 30 to 65 °C, respectively.

Shalaby and Bek [62] constructed an FCISD integrated with plastic cylinders packed with paraffin wax (liquefying temperature of 49 °C) under the trays of the drying chamber. It is found that T_{dc} could be maintained from 2.5-7.5 °C greater than T_{amp} for seven hours after the sunset. The final MC of herbs such as T. Neriifolia and O. Basilicum was reached by 18 and 12 h, respectively.

Komolafe et al. [63] carried out experiments on an FCISD with gravel as SHS while drying locust beans under natural and forced modes. The drying characteristics are found to be in accordance with the Lewis model for both modes. The D_{ef} was estimated as 1.823×10^{-11} and 2.735×10^{-11} m^2/s, in both dryers. The drying time was saved by 6 h in forced mode.

Vijayan et al. [64] implemented exergy and environmental analysis on FCISD with pebble as SHS material that was located under the absorber sheet of SAC while drying bitter-gourd slices. The value of average $\eta_{ex,dc}$ was from 28.27−40.68%. The environmental analysis was conducted for different lifespans of ISD. The EPBP was 2.21 years.

Bhardwaj et al. [65] also did a similar analysis with sensible and latent heat storage (LHS) units during drying of valerian rhizomes. The average $\eta_{\mathrm{en},SAC}$ and $\eta_{ex,SAC}$ were 26.1% and 0.81% with storage and 9.8% and 0.14% without storage, respectively. The $\eta_{ex,dc}$ was in a range of 3.7−75.15% with an average of 30.28%.

Chaatouf et al. [66] dealt an analysis to examine the dynamic and thermal characters of the NCISD integrated with the PCM-filled copper tubes which were located on the side of the setup using CFD analysis. The $\eta_{en,dry}$ was increased by 3.12% during the shine-off time compared to without a storage system. Paraffin RT58 gave nice output than RT24 and Gallium and it increased the temperature difference by 11 °C at night.

Yadav and Chandramohan [30] concluded that finned copper tubes gained maximum heat compared to those without fins in a TES device in a drying chamber. The temperature difference of the air in concentric tubes was found to be 9.1 and 5.47 °C for with and without fins on copper tubes, respectively.

2.4. Studies on some fruits and vegetables in dryers

The various studies performed on selected food products in dryers are presented in this section. Santos et al. [67] studied the influence of ultrasound pre-treatment for 0, 10 and 20 minutes during drying of guava pieces in a hot air oven. It is observed that with a 20-minute pretreatment of ultrasound, the guava slices were dried 5 h earlier than without pretreatment. The drying kinetics were studied at 50, 70 and 90 °C.

Vijayrakesh et al. [68] developed a DSD dryer consisting of polycarbonate dome, galvanized iron sheet as floor including PCM, stainless steel trays and exhaust fan. The peak temperature inside the chamber was improved due to PCM by 7.81%, 3.125%, 8.33% and 4.55% during drying of guava, coconut, okra and banana, respectively.

Gokhale and Lele [69] conducted drying experiments using beetroot slices in a hot air dryer by varying the temperatures between 50 and 120 °C. The MC of beetroot was reduced to 0.04 from 8.5 db in a duration of 105 and 360 minute when the drying temperature was constantly maintained at 120 and 50 °C. A new drying model was proposed and found to be fitting model for all temperatures of hot air dryer.

Malakar et al. [70] dried beetroot slices in an evacuated tube ISD with evacuated tubes and OSD method. Weibull model was found to be suited model in the dryer. The MC of beetroot decreased from 5.26 to 0.102 and 0.157 db in the solar dryer and OSD, respectively. The average D_{ef} and activation energy (E_{ac}) for beetroot slices in the dryer were observed as 1.94×10^{-7} m^2/s and 27.60 kJ/mol, respectively.

Hossain and Bala [71] dried the green chilli in a solar tunnel dryer combined with SAC. The average temperature in the dryer was maintained 21.62 °C higher than atmosphere. The sample achieved a final MC in 22 h and 35 h, in the dryer and OSD, respectively. The quality of chilli dried in the dryer found to be better than OSD.

Gupta et al. [72] examined the drying behaviour of green chillies and performance analysis of the hybrid type PVT dryer. In the dryer and OSD, the final MC of green chilli was noticed to be 0.45 and 1.15 db, from an initial MC of 4.0 db, respectively, with a duration of 8 h. The accurate models to describe the drying behaviour of green chilli in the dryer and OSD were modified Henderson and Pabis and Two-term exponential model, respectively. The $\eta_{en,dry}$ was estimated as 18.81%, respectively.

2.5. Conclusions from literature review

From the literature review, it is observed that various analyses have been carried out in various solar dryers with and without TES. The drying kinetics of different food products were studied in various solar dryers such as DSD [25, 26], MSD [12, 29], HSD [27] and ISD (natural [41–43] and forced [38, 39]) without storage. The drying kinetics such as MC, moisture ratio, drying rate and D_{ef} were evaluated in solar dryers. These properties were determined for different food products such as brinjal [32] , bitter gourd [64], apricot [51], mango [32], turmeric [37, 43], ginger [50], coconut [48], potato [47], carrot [73] and red chilli [22] which are similar to the selected food products (guava, muskmelon, beetroot and green chilli) in solar dryers. It is also observed that evaluation of drying models for various food products had been done in different solar dryers [12, 25, 26, 31, 35, 36, 38]. It is noticed that some works are reported on developing numerical models [23, 66] and thermodynamic analysis [29, 52] of solar dryers.

Table 1 describes the various properties of the food products before and after drying in different drying methods include ISD, solar tunnel dryer, hot air drying and MSD. The total sugars were increased in food products after drying due to removal of moisture and increased concentration effect per unit mass of the product [75, 76]. The acidity, total soluble solids, total phenolic content, total flavonoids content, antioxidant activity, vitamin C and colour were decreased in food products due to oxidative degradation in the presence of heat during drying process [29,77]. The prolonged duration and direct exposure of fruits to UV radiation in open sun drying enables more losses in the above properties when compared to ISD [26,77].

Table 1.1. Properties of the food products before and after drying in different drying methods

Fruit	Property	Before drying (Fresh)	After drying	Method of drying
Pineapple	Total sugars (g/100 g)	15.7 ± 0.1	24.2 ± 0.3	ISD [26]
	Acidity (%)	3.4 ± 0.01	1.8 ± 0.02	
	Total phenolic content (mg/ 100 g)	0.43 ± 0.02	0.41 ± 0.03	
	Vitamin C (mg/100 g)	23.4 ± 0.2	22.1 ± 0.2	
Mango	Total sugars (g/100 g)	9.1 ± 0.3	14.3 ± 0.3	ISD [26]
	Acidity (%)	0.53 ± 0.02	0.24 ± 0.02	
	Total phenolic content (mg/ 100 g)	0.85 ± 0.02	0.75 ± 0.03	
	Vitamin C (mg/100 g)	36.4 ± 0.2	35.6 ± 0.4	
Banana	MC (kg/kg of dry basis)	3.093	-	solar tunnel dryer [75]
	Total sugars (%)	19.22 ± 0.03	45.96 ± 0.02	
	Vitamin C (mg/100 g)	20.6 ± 0.16	5.32 ± 0.18	
Papaya	MC (kg/kg of dry basis)	16.153	-	solar tunnel dryer [75]
	Total sugars (%)	8.17 ± 0.04	51.27 ± 0.25	
	Vitamin C (mg/100 g)	68 ± 2.16	15.13 ± 0.50	
Ginger	Total phenolic content (mg/g)	11.97	9.69	Hot air drying at 60 °C [78]
	Total flavonoids content (mg/g)	13.49	12.08	

	Antioxidant activity (mg/g)	64.45	62.22	
	Vitamin C (mg/g)	3.49	3.37	
Pomegranate seeds	Sugars (Glucose) (g/100g)	27.1	15.7	Hot air drying at 50 °C [76]
	Citric acid (g/100g)	10.5	5.06	
	Total phenolic content (mg/g)	7.57	2.05	
	Antioxidant activity (mg/g)	1.20	0.70	
Red pepper	Acidity (%)	0.358	0.113	Hot air drying at 50 °C [29]
	Total soluble solids (°B)	11.33	4.2	
	Total phenolic content (mg/ 100 g)	1359	237	
	Antioxidant activity (µg/mg)	276.9	2225.6	
	Vitamin C (mg/g)	188.59	32.61	
Black turmeric	Moisture content (kg/ kg of dry basis)	2.759	0.093	MSD [77]
	Total phenolic content (mg/g)	21.49	8.67	
	Total flavonoids content (mg/g)	10.99	7.59	
	Antioxidant activity (µmol/g)	47.98	28.33	

The drying kinetics help to determine the drying time of food products [35, 38]. The drying kinetics such as D_{ef}, heat and mass transfer coefficients (h_{ht} and h_{mt}), and E_{ac} were not evaluated during the drying of guava, muskmelon, beetroot and green chilli in ISD. The forced convection improves the performance of ISD dryers compared to natural convection [28, 67]. Very few studies are available on FCISD [45–47] by installing fans or blowers but they were powered by electrical energy from the grid at the entry of SAC. The FCISD setup can be made by fixing fans near the entry of SAC and these can be run by solar energy itself without any electrical energy [51]. The use of solar PV panels in the setup enables drying process an energy-efficient.

The literature survey summarised that drying kinetics were evaluated on solar dryers integrated with various storage materials. The SHS materials such as pebble [41, 45, 57], gravel [63], concrete [41, 43], sand [41, 50, 52], limestone [57], water [47–49, 54] and engine oil [65] were used in solar dryers while drying various food products. Mostly, the paraffin wax [10, 38, 40, 47, 49, 51] was used for LHS in different solar dryers since it has excellent thermo-physical properties than other LHS materials. The TES unit was kept in different places such as under the absorber plate [10, 50, 52, 56, 57] in the drying chamber [44, 51, 55] and in a separate heat exchanger [48, 53, 54, 68] in various solar dryers. It is found that very few studies kept the TES unit in the drying chamber of ISD as it produced a better dryer performance [51, 55]. The usage of fins on the inner tubes of the TES unit increases the heat gain of PCM [30]. The drying time was saved due to the usage of the TES unit in the solar dryer [10, 42, 46, 53]. Very few studies performed the comparative study on drying kinetics without and with TES unit in the ISD [50, 69]. The important drying kinetics such as D_{ef}, h_{ht}, h_{mt} and E_{ac} were not extensively studied in the ISD without and with TES. There is no study found on FCISD integrated with divergent duct consisting of DC fans governed using solar PV panels with TES device.

The extensive literature review also confirmed that studies reported on EEA of various solar dryers without TES [23, 24, 26, 28, 29, 33, 36] and with TES [42, 48, 49, 53, 54]. While doing EEA the specific moisture extraction rate (SMER) was not evaluated in ISDs, which describes the amount of moisture removed per given input solar radiation [65]. It helps to analyse how effectively drying happened and also evaluate the effectiveness of the drying process. Some studies were also reported on exergy-environmental [28, 57] and exergy-economic analysis [40, 70] of solar dryers. Studies are available on exergy analysis of SACs [46, 71], but few studies are available in the specific area of indirect solar dryers [57, 58] which is necessary to get maximum air temperature at collector exit. In EEA analysis, the existing studies [52, 53] focused on exergy analysis of the drying chamber in ISDs. There is limited data [52, 57] on exergy sustainability indicators (improvement potential (IP), sustainability index (SI) and waste exergy ratio (WER)) for detailed exergy analysis of solar dryers as these parameters help to identify the percentage of exergy losses and are used to optimise the drying process by reducing losses. The sustainability indicator such as environmental impact factor (EIF) was not evaluated in ISD, which is important to know the environmental damage of setup, loss of exergy [84]. Very few studies [73, 74] are available on detailed energy and exergy analysis on FCISD powered by solar PV panels. Very few studies [53, 57, 58] were available on EEA on FCISD with TES materials.

2.6. Literature gaps

The literature on different solar dryers is reviewed and found that ISD is advantageous than other solar dryers. The drying kinetics of food products in NCISD and FCISD dryers and EEA of NCISD and FCISD without and with storage are reviewed and few literature gaps are found as follows.

- Few studies are available on FCISD [45–47][44–46][44–46][43–45][42–44][41–43][40–42][39–41]by installing fans or blowers powered by electrical energy from the grid at the entry of SAC.
- It was found that guava, muskmelon, beetroot and green chilli were not dried in ISD. The drying models (which is essential for drying industries and researchers) of guava, muskmelon, beetroot and green chilli are not estimated in the ISDs.
- The drying kinetics such as effective diffusion coefficient, heat and mass transfer coefficients and activation energy were not evaluated during the drying of guava, muskmelon, beetroot and green chilli in ISD.
- There is no experimental study reported on DC fans powered by solar PV panels installed at the inlet of SAC in ISD.
- There is no comparative study found on NCISD and FCISD during drying of guava, muskmelon and beetroot.
- It is found that very few studies kept the TES device consist of paraffin wax in the drying chamber as it produced a better dryer performance

- There is no experimental study found on ISD using TES device consist of fins on inner tube of concentric tube in the drying chamber.
- There is no comparative study conducted on FCISD powered by PV panels without and with a TES device while drying guava, muskmelon, beetroot and green chilli.
- Very few studies reported exergy analysis of SAC while studying EEA of ISD
- Very few studies reported data on exergy sustainability indicators such as improvement potential, environmental impact factor, sustainability index and waste exergy ratio for detailed exergy analysis of solar dryers
- There is no study found on EEA analysis during the drying of guava, muskmelon and beetroot on FCISD powered by PV panels. There is no comparison data available in the literature on EEA analysis of NCISD and FCISD.
- There is no comparative study found on EEA analysis during drying of guava, muskmelon, beetroot and green chilli on FCISD powered by PV panels without and with TES in the drying cabinet.

2.7. Specific objectives

Based on the above-mentioned literature gaps and conclusions from the literature review, the following specific objectives under the major objectives (described in **Chapter 1)** are describe to fulfil the literature gaps of the existing literature:

The specific objectives under Major objective 1 are

- To estimate the dimensions of TES cell and TES device based on the literature.
- To develop a TES cell, consist of aluminium inner tube and polycarbonate outer tube.
- To develop a TES device and install in the drying chamber of ISD.

The specific objectives under Major objective 2 are

- To examine transient temperature distribution of solar air collector (SAC) and drying chamber in NCISD and FCISD during drying guava, muskmelon and beetroot.
- To determine the drying kinetics such as moisture content (MC) vs time data, drying rate and moisture ratio for both NCISD and FCISD.

- To evaluate thermal properties such as effective diffusion coefficient (D_{ef}), heat and mass transfer coefficients (h_{ht} *and* h_{mt}), and activation energy (E_{ac}) in NCISD and FCISD.
- To find proper drying models to fit the drying data of guava, muskmelon and beetroot in NCISD, FCISD and open sun drying (OSD)

<u>The specific objectives under Major objective 3 are</u>

- To investigate energy analysis of SAC and drying chamber by finding parameters such as energy efficiency of collector ($\eta_{en,SAC}$), energy efficiency of dryer ($\eta_{en,dry}$), specific energy consumption (SEC) and specific moisture extraction rate (SMER) in NCISD and FCISD.
- To determine exergy input, output, losses and efficiencies for SAC and drying chamber in NCISD and FCISD.
- To evaluate exergy sustainability indicators such as improvement potential (IP), environmental impact factor (EIF), sustainability index (SI) and waste exergy ratio (WER) of the drying chamber in NCISD and FCISD.
- To perform a comparative analysis of the parameters in NCISD and FCISD dryers

<u>The specific objectives under Major objective 4 are</u>

- To examine transient temperature distribution of SAC and drying chamber in FCISD without (model-1) and with TES (model-2) during drying guava, muskmelon, beetroot and green chilli.
- To determine the drying kinetics such as MC vs time data, drying rate and moisture ratio for model-1 and model-2
- To evaluate thermal properties such as D_{ef}, h_{ht}, h_{mt}, and E_{ac} in model-1 and model-2
- To find proper drying models to fit the drying data of guava, muskmelon, beetroot and green chilli in model-1 and model-2.

<u>The specific objectives under Major objective 5 are</u>

- To investigate energy analysis of collector and drying chamber by finding parameters such as $\eta_{en,SAC}$, $\eta_{en,dry}$, SEC and SMER in model-1 and 2.
- To determine exergy input, output, losses and efficiencies for SAC and drying chamber in model-1 and model-2.

- To evaluate exergy sustainability indicators such as IP, EIF, SI and WER of the drying chamber in model-1 and model-2.
- To perform a comparative analysis of the parameters in model-1 and model-2.

Chapter 3

Methodology

Chapter 3

3. Methodology

3.1. Introduction

This chapter is related to methodology of experimental work. The working principle of ISD with TES and components of NCISD and FCISD dryers are explained. The FCISD setup with TES components is explained. The measuring instruments used in the experimentation are explained. The preparation of samples and experimental procedures are explained to conduct experiments on NCISD and FCISD dryers without TES and FCISD without and with TES. The initial MC of the food products used in the present study are discussed. The equations used to evaluate the drying kinetics and EEA of dryers are explained. The uncertainty analysis of parameters is also presented.

3.2. Working principle of ISD with TES

The solar radiation falls on SAC, transmit through window glass and gets absorbed by absorber plate. In the SAC, air gets heated by absorbing heat from absorber plate and enters into the drying chamber. The heated air flows through TES device and food products placed on the trays of the drying chamber. The warm air absorbs the moisture from food products and exit through chimney. The TES device stores and releases the heat energy, which enables continuous drying during off-sunshine hours. The working principle, components of FCISD and locations of instruments are shown in **Fig. 3.1**.

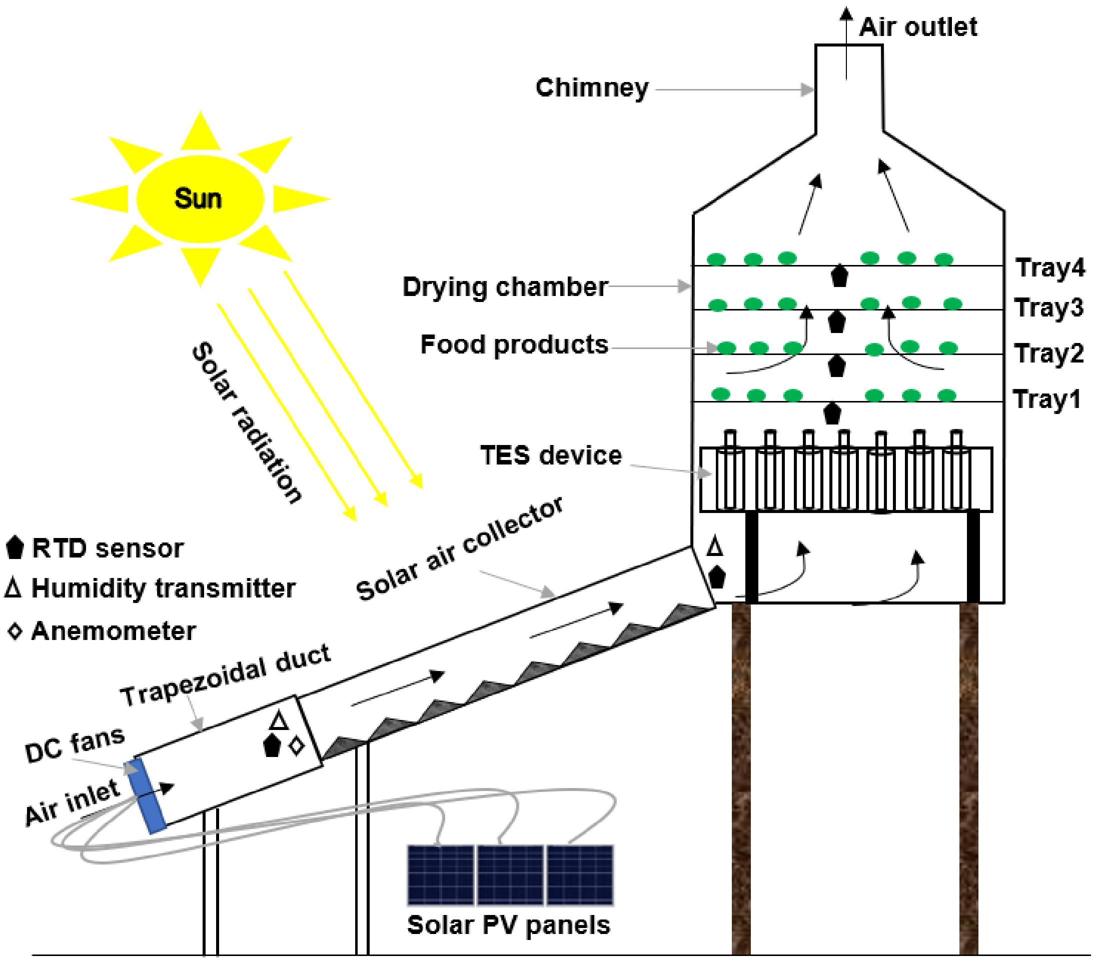


Fig. 3.1. Schematic diagram of FCISD with TES

3.3. Description of experimental setup

An NCISD was designed and fabricated at National Institute of Technology Warangal, India (Longitude: 79.58° E, Latitude: 18° N). The NCISD consists of a SAC, drying chamber and an exhaust chimney as shown in **Fig. 3.2 (a).** SAC is oriented at an angle of 30° with respect to horizontal surface facing North – South direction based on the latitude of Warangal, India (18° N). It consists of glass, corrugated absorber plate of V shape and rockwool insulation to prevent heat losses. The absorber plate is made of copper because it has high thermal conductivity. The absorber plate has a thickness of 1 mm and is coated with black paint to increase the absorptivity of the material. V – corrugations are provided on the absorber plate to increase the surface area and thereby increase the radiation incident on it. Also, it is useful to enhance the turbulence of air flow inside SAC. To provide forced convection, a divergent duct (trapezoidal duct) was attached with direct current (DC) fans driven by PV panels installed before the entry of SAC (**Fig. 3.2. b**). The uniform flow is not maintained in the SAC and trapezoidal duct was used to encourage nozzle effect at inlet of the SAC. In the ISD, the heated air from the SAC flows over the trays inside the drying cabinet, absorbs moisture from the food products.

A trapezoidal shaped duct is fixed at the entrance of SAC, which is fabricated using galvanised iron (GI) sheet metal with a thickness of 3 mm. Three DC fans (7.5 cm diameter, 12 V, 0.25A) are fixed at the entrance of the duct to enhance air flow. These fans were taken from scrap computers. The duct has gross dimensions of 0.4 m × 0.1 m at the entrance, 1 m × 0.07 m at the rear end and a length of 0.5 m as shown in **Fig. 3.3.**

(a) (b)

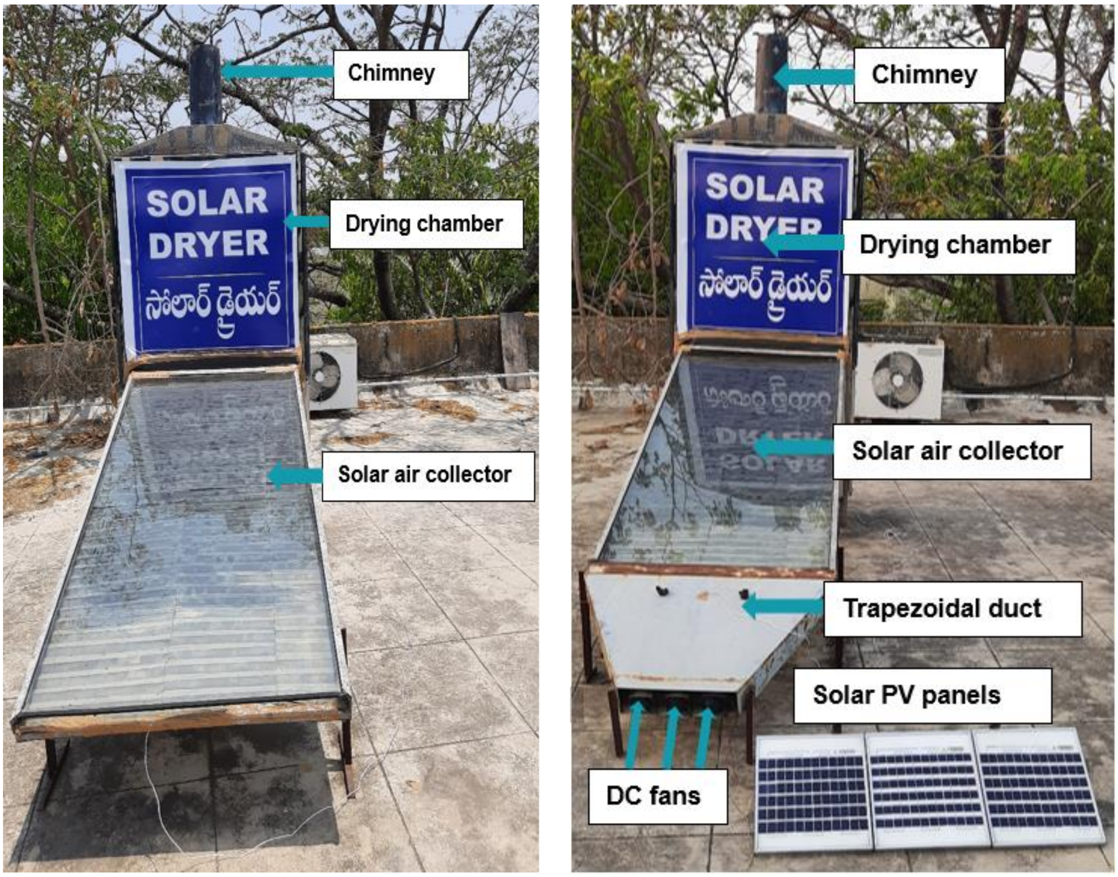


Fig. 3.2. The experimental setup of (a) NCISD and (b) FCISD

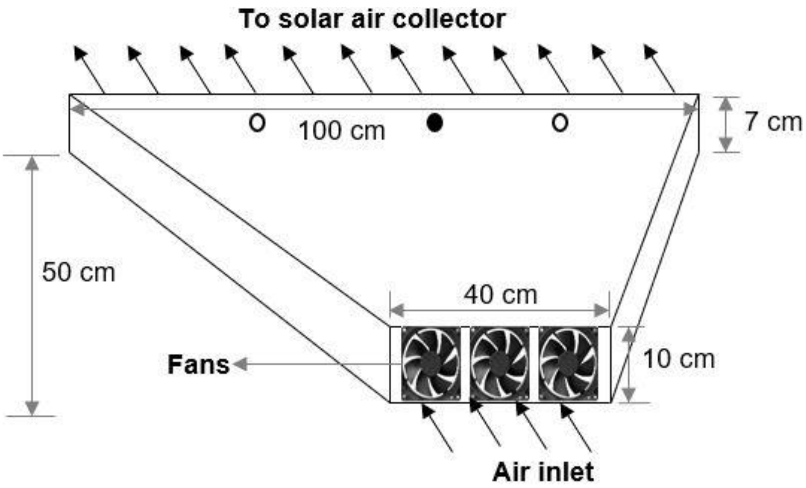


Fig. 3.3. Schematic diagram of Trapezoidal duct

3.4. Development of TES device in the drying chamber

The TES device consist of TES cells. The TES cells are fabricated to store and release the thermal energy using the paraffin wax (no caking, CAS No.: 8002-74-2, EC No.: 232-315-6, melting point: 56-60 °C). The TES cell is a concentric tube consists of inner aluminium pipe and outer polycarbonate pipe. The paraffin wax was filled in the annulus of concentric tube or TES cell. The aluminium material is selected because it is cheaper than copper material and also the corrosion rate of aluminium-paraffin wax is lower than copper-paraffin wax [87].The aluminium tubes having inner diameter of 16 mm are taken based on the availability. The length of TES cell was taken as 300 mm for efficient heat transfer from fluid to aluminium and paraffin wax as reported in the literature [55, 76].

Ismail and Goncalves [89] suggested that a ratio of 4 (diameter of outer tube/diameter of inner tube) is best as it gives the highest effectiveness. The thickness of fins was taken as inner tube wall thickness to get higher efficiency and heat transfer rate [90]. It is also reported in the literature that ratio of 0.8 (diameter of fin/diameter of outer tube) is the optimum for better efficiency [91]. The fins near the bottom of TES cell taken as 8.16 mm to avoid collecting solid PCM [88] and total 10 number of fins selected depending on the fabrication viability. First aluminium tubes are taken and circular fins are welded on the aluminium tube. Next polycarbonate pipes of 300 mm were taken and attached at the bottom and top of the aluminium tube by caps. A 50 number of TES cells are fabricated based on the available area of the drying chamber. Next, the rectangular TES device is fabricated using six polycarbonate sheets to accommodate 50 TES cells. The dimensions of TES device and TES cell are shown in **Fig. 3.4.** The paraffin wax is melted on the hot plate (**Fig. 3.5. a**), poured in the annulus of TES cell using funnel (**Fig. 3.5 b**) and cooled down to solidify the PCM (**Fig. 3.5 c**). Similarly, 50 number of TES cells were made and put in the TES device and TES device was kept below the trays of the drying chamber as shown in **Fig. 3.6.**

(a) (b)

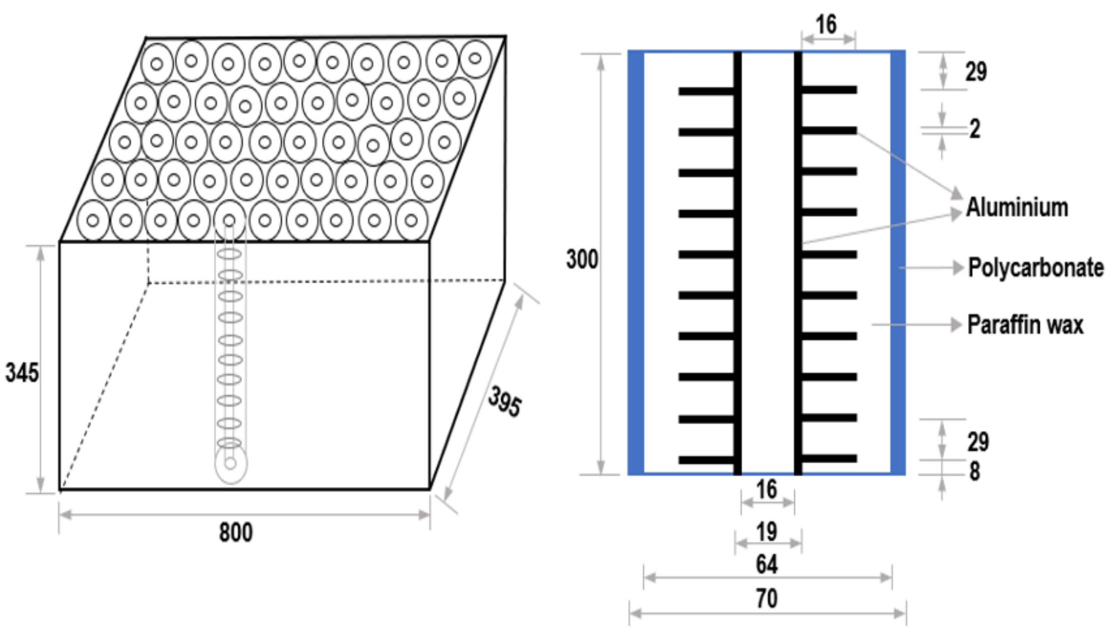


Fig. 3.4. Schematic diagram of (a) TES device and (b) TES cell or concentric tube

(a) (b) (c)

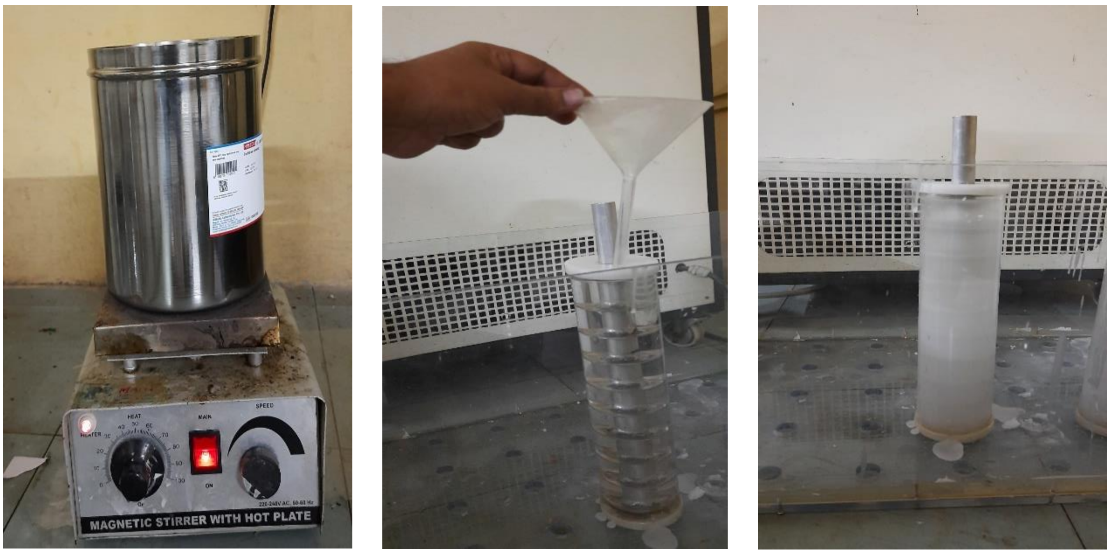


Fig. 3.5. (a) heating the PCM on hot plate (b) Pouring melted PCM in TES cell (c) solidified PCM in TES cell

Fig. 3.6. The actual TES device in the drying chamber

3.5. Components of ISD and their specifications

In this section, the components and accessories of ISD with specification are given in **Table 3.1.** The FCISD consists of trapezoidal duct, SAC, drying chamber and chimney. The SAC consists of glass cover, absorber plate and insulation. The dimensions of the SAC were estimated by considering the average solar radiation of NIT Warangal as 700 W/m^2 and 30° collector angle with horizontal [92]. The solar radiation pass through glass cover and absorb by the absorber plate made of copper with V-corrugations. The air gets heated in the SAC and enter into the drying chamber. The window glass of 5 mm thickness (transmissivity= 0.88) is used to reduce the top heat losses in SAC and transmission of solar radiation through it [93].

The copper absorber plate is selected due to its high thermal conductivity and it is blackened to increase the absorptivity [94]. The copper plate has thickness of 1 mm is selected to get higher absorber plate temperature since absorber plate temperature decreases with increasing thickness from 1 mm [95]. The absorber plate has V-shaped corrugations to enhance its surface area and the radiation incident on it [96]. The rockwool is taken as insulating material due to its lower thermal conductivity (0.035 W/mK) and it is placed below the SAC to avoid heat loss. The rockwool of thickness 2.5 cm is taken as collector efficiency not increased much from 2 to 3 cm thickness of rockwool [97]. The SAC is fitted with an angle of 30° to receive maximum radiation, since researchers suggested that tilt angle should be equal to the latitude (18 °N) plus 10 to 15° to get maximum radiation [98]. The trapezoidal duct is designed to put 3 DC fans at the front end and SAC at the rear end. Since each fan has 12 V capacity, 17 V capacity solar panels were selected. The drying chamber was made with GI sheets with dimensions of 0.85 m × 0.4 m × 1.05 m to ensure uniform distribution of air flow by providing sufficient gap between drying chamber inlet, trays and drying chamber outlet [64]. The trays were made with wooden frames and plastic mesh to ensure that trays shouldn't absorb any thermal energy because wooden frames have lower thermal conductivity (0.1 to 0.2 W/mK). The trays with dimensions of 0.8 m × 0.3 m were designed after keeping thermocol sheets of 5 cm on the sides of the drying chamber to prevent heat losses. The convergent section is designed at the end of drying chamber and chimney is provided to leave the air from drying chamber without pressure loss [99]. The TES device is fabricated to store the thermal energy in sunshine hours and release it in non-sunshine hours. The design of TES device is explained in the previous section (3.4. Development of TES device in the drying chamber). To find the initial MC of food products, the food products were placed in the hot air oven (**Fig. 3.2 b**) for 24 hours at 105 °C and initial and final masses were recorded.

Table 3.1. Components and accessories of ISD with their specifications

S.No.	Components	Specifications
1.	Gross dimensions of SAC	2 m × 1.05 m × 0.125 m
2.	Absorber plate	2 m × 0.9 m of corrugated V-shape with black colour coating
3.	Absorber material	1 mm copper plate
4.	Glazing material	5 mm window glass
5.	Insulation for SAC	2.5 cm rockwool

6.	SAC tilt angle	30° (with horizontal)
7.	Gross dimensions of drying chamber	0.85 m × 0.4 m × 1.05 m
8.	Dimensions of tray	0.8 m × 0.3 m
9.	Material for tray	wood framed plastic mesh
10.	3 solar PV panels	0.03 m × 0.03 m (10 W and 17 V)
11.	3 DC CPU fans	diameter of 7.5 cm (12 V and 0.25 A)
12.	Mode of air flow	natural or forced convection
13.	Material for TES device	Polycarbonate sheets
14.	Gross dimensions of TES device	0.85 m × 0.4 m × 1.05 m
15.	Material for TES cell	Polycarbonate and aluminium tubes with fins
16.	TES material	Paraffin wax (no caking, CAS No.: 8002-74-2, EC No.: 232-315-6, melting point: 56-60 °C, HIMEDIA, India)
17.	Hot air oven	PPI make (230V, 3500W,15A, 0-250 ℃)

3.6. Instruments used in the experiments

Table 3.2 shows the instruments which were used during experiments and their specifications. Mass reduction of the samples was measured using electronic weighing balance (**Fig. 3.7 a**). Let T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} be the temperature at atmosphere, collector inlet, collector outlet, trays-1, 2, 3 and 4, respectively. RTD sensors (**Fig. 3.7 c**) were used to measure temperature at a location in ISD. The RTD sensors were attached to 16 channel datalogger (**Fig. 3.7 d**) to record and store the data of temperatures. Solar power meter (**Fig. 3.7 e**) was used to measure solar radiation. Humidity transmitter and anemometer (**Fig. 3.7 f**) was used to measure relative humidity and velocity of air.

Table 3.2. Instruments used during experiments with their specifications

Name of instrument	**Model and brand**	**Specification**	**Accuracy**

Electronic weighing balance	OHAUS PA 214, USA	0-200 g	± 0.2 mg
RTD Pt-100 sensor	PPI Make-India	0-400 °C	±1 °C
16 channels data logger	PPI Make-India	-	± 25%
Solar power meter	Tenmar TM 207-Taiwan	0-200 W/m^2 -20 to 80 °C	±10 W/m^2
Humidity transmitter	Testo 635-India	RH (0−100%)	± 2%
Hot wire anemometer	Testo 635-India	0−20 m/s -20−70 ºC	± 0.03 m/s ± 0.3 ºC

(a)

(b)

(c)

(d) (e) (f)

Fig. 3.7. Snapshot of (a) electronic weighing balance (b) hot air oven (c) RTD sensors (d) data logger (e) solar power meter (f) humidity transmitter and anemometer

3.7. Experimental procedures

In this section, the experimental procedure to conduct experiments on NCISD and FCISD dryers without TES device and measuring parameters were explained. Next, the experimental procedure to conduct experiments on FCISD without and with TES device and measuring parameters were explained.

3.7.1. Procedure for drying in NCISD and FCISD without TES device

On the day of experiment, food products (Guava, muskmelon and beetroot) were purchased from local market from Warangal. Guava and beetroot were sliced into 5 mm thickness and muskmelon were sliced into 10 mm thickness. In the experiments, 200 g of slices were put on each tray of the drying chamber and another 200 g of slices were used for open sun drying (OSD). The experiment was performed from 08:00 am to 05:00 pm, with a duration of 9 hours in a day. Initially, the experiments were conducted on NCISD. Next, a trapezoidal duct was added with the existing NCISD setup to conduct experiments on FCISD. Next, the mass of the samples was measured by a weighing balance at every hour in both the ISD setups and OSD method. The other measured parameters during experimentation were; solar radiation, temperature, relative humidity and velocity of air. The RTD sensors were located at atmosphere, collector inlet, collector outlet and four trays of drying chamber were used to record temperatures in data logger. The velocity at collector inlet, and relative humidity at collector inlet and outlet were measured by Testo 635, India. The drying kinetics and energy and exergy analysis of NCISD and FCISD without TES device are evaluated during drying guava, muskmelon and beetroot from experimental readings.

3.7.2. Procedure for drying in FCISD without and with TES device

Initially the drying experiments were conducted on FCISD without TES device (model-1) by keeping 200 g of guava, muskmelon, beetroot and green chilli on each tray of drying chamber (**Fig. 3.8**) and another 200 g for OSD. Next, the experiments were conducted on FCISD with TES device (model-2). In model-2, the experiments performed from 8.00 am to 12.00 am, with a duration of 16 hours in a day. In model-2, additionally paraffin wax temperature was measured at five places in TES cell by RTD sensors. The drying kinetics and energy and exergy analysis of FCISD without and with TES device are evaluated during drying guava, muskmelon, beetroot and green chilli from experimental readings.

(a) (b)

(c) (d)

Fig. 3.8. Snapshot of fresh (a) guava (b) muskmelon (c) beetroot (d) green chilli samples on trays of drying chamber

3.8. Determination of initial moisture content

The initial MC (MC_i) of samples (guava, muskmelon, beetroot and green chilli) was estimated using hot air oven method. A total of 12 sample pieces were placed in hot air oven and dried continuously for 24 h at a temperature of 105 °C as per ASTM standards. The initial and final masses of the samples were measured by electronic weighing balance. The average initial MC of 5 random samples is found and taken as initial MC for guava, muskmelon, beetroot and green chilli as reported in **Tables 3.3, 3.4, 3.5** and **3.6**, respectively. The MC in wet basis (wb) and dry basis (db) is estimated using [92];

$$MC(wb) = \frac{m_i - m_d}{m_i} \quad (1a)$$

$$MC(db) = \frac{m_i - m_d}{m_d} \quad (1b)$$

Where, m_i *and* m_d is initial and final dried mass of the sample, respectively

Table 3.3. Initial MC of guava slices

S. No.	Initial mass, (g)	Final mass, (g)	Initial MC (kg/kg of wb)	Initial MC (kg/kg of db)

1	17.2123	2.6564	0.8456	5.4795
2	16.5385	2.5254	0.8473	5.5489
3	18.6170	2.7925	0.8500	5.6667
4	18.2122	2.7880	0.8469	5.5323
5	19.9471	3.0926	0.8449	5.4499
Avg.			**0.8469**	**5.5355**

Table 3.4. Initial MC of muskmelon slices

S. No.	**Initial mass, (g)**	**Final mass, (g)**	**Initial MC (kg/kg of wb)**	**Initial MC (kg/kg of db)**
1	7.0345	0.5223	0.9258	12.4683
2	7.0560	0.5138	0.9272	12.7330
3	7.3620	0.5662	0.9231	12.0025
4	7.0511	0.5260	0.9254	12.4051
5	7.4378	0.5514	0.9259	12.4889
Avg.			**0.9255**	**12.4156**

Table 3.5. Initial MC of beetroot slices

S. No.	**Initial mass, (g)**	**Final mass, (g)**	**Initial MC (kg/kg of wb)**	**Initial MC (kg/kg of db)**
1	16.686	1.9235	0.88472	7.6748
2	11.6707	1.3294	0.88609	7.7789
3	22.4205	2.5034	0.88834	7.9560
4	12.8210	1.4986	0.88311	7.5553
5	19.6509	2.2303	0.88650	7.8109
Avg.			**0.88576**	**7.7535**

Table 3.6. Initial MC of green chilli

S. No.	**Initial mass, (g)**	**Final mass, (g)**	**Initial MC (kg/kg of wb)**	**Initial MC (kg/kg of db)**

1	5.2214	0.5477	0.8951	8.5333
2	5.4161	0.5658	0.8955	8.5724
3	5.1916	0.5667	0.8908	8.1611
4	5.0105	0.5434	0.8915	8.2206
5	4.9341	0.5191	0.8948	8.5051
Avg.			**0.8936**	**8.3985**

3.9. Equations employed

3.9.1. Drying kinetics

The drying rate (DR) of the food product in ISD is calculated based on the ratio of the difference in two successive MCs and time difference (dt) and it is expressed as [38];

$$DR = \frac{dMC}{dt} = \frac{MC_{t+dt} - MC_t}{dt} \tag{2}$$

The moisture ratio (MR) [100] was estimated as;

$$MR\ (db) = \frac{MC_{ts}}{MC_i} \tag{3}$$

Where, MC_{ts} is the MC at a given time, t (db).

There are various empirical models presented in the existing studies for defining the drying characters of fruits and vegetables. In the present study, 12 empirical models were selected as shown in **Table 3.7**.

Table 3.7. Empirical drying relations

S.No.	Model Name	Expression	Reference
1	Page model	$MR = \exp\,(-kt\text{^}n\,)$	[36]
2	Lewis or Newton	$MR = \exp\,(-kt)$	[59]
3	Modified Page model	$MR = \exp\,(-(kt)\text{^}n\,)$	[41]
4	Wang and Singh	$MR = 1 + at + bt\text{^}2$	[100]
5	Henderson and Pabis	$MR = a\,exp(-kt)$	[80]

6	Logarithmic	$MR = a\, exp(-kt) + c$	[41]
7	Two-term	$MR = a\, exp\,(-kt) + b\,\exp(-gt)$	[100]
8	Midilli and Kucuk	$MR = a\, exp\,(-kt\text{^}n\,) + bt$	[80]
9	Simplified Fick's diffusion	$MR = a\,\exp\,(-k(t\,/\,l\text{^}2\,))$	[38]
10	Diffusion approach	$MR = a\,\exp\,(-kt) + (1 - a)\ \exp\,(-kbt)$	[59]
11	Two-term exponential	$MR = a\,\exp\,(-kt) + (1 - a)\ \exp\,(-kat)$	[80]
12	Verma model	$MR = a\, exp\,(-kt) + (1 - a)\ \exp\,(-gt)$	[59]

The models mentioned above are fitted with the present experimental data using OriginPro 2018 software. The goodness of fit was examined by statistical parameters including coefficient of determination (R^2) and reduced chi-square (χ^2) [101] and these are estimated by;

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(MR_{exp,i})^2} \quad (4)$$

$$\chi^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N-F} \quad (5)$$

Where, N and F are the total number of experiments and constants, respectively. The highest value of $R^2$and lowest value of χ^2 represent the perfect fitting to the model from the experimental data.

Effective diffusion coefficient (D_{ef}) (m^2/s) can be estimated from Fick's diffusion equation [38] ;

$$\frac{\partial MR}{\partial t} = D_e \nabla^2 MR \quad (6)$$

The simplified solution has been proposed by Crank [102] by assuming negligible shrinkage, uniform thickness and uniform initial moisture distribution and it is expressed as;

$$MR = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}exp\left[-\frac{(2i+1)^2\pi^2 D_{ef}t}{4B^2}\right] \quad (7)$$

Where, B is the thickness of the food product.

After considering the first term of the series, D_{ef} was determined by the following equation [12];

$$MR = \frac{8}{\pi^2} exp\left[-\frac{\pi^2 D_{ef} t}{4B^2}\right] \tag{8a}$$

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{ef} t}{4B^2} \tag{8b}$$

The heat and mass transfer coefficients (h_{ht} and h_{mt}) are surface properties of the materials which need to be estimated as these influence drying rate and account for the physics of drying. h_{mt} (m/s) in the material in terms of MR can be estimated using [103];

$$h_{mt} = \frac{V}{A_s t}\ln(MR) \tag{9}$$

where, A_s and V are the surface area and volume of the food product, respectively.
By the Lewis-analogy, the h_{ht} (W/m^2K) is calculated by [92];

$$h_{ht} = h_{mt}\left(\frac{k_{da}}{D_{AB} Le^{1/3}}\right) \tag{10}$$

where, D_{AB} is the diffusion coefficient of water in the air and k_{da} is the thermal conductivity of drying air (W/m^2K), Lewis number (Le) is calculated from $Le = \frac{\alpha_{da}}{D_{AB}}$. where, α_{da} is the thermal diffusivity of drying air (m^2/s).

The activation energy (E_{ac}) is determined by the Arrhenius equation which represents D_{ef} as a function of temperature [73]. The graph is drawn between ($\ln D_{ef}$) and ($1/T$+273.15) and best fitting curve fitting gives the value of E_{ac}.

$$D_{ef} = D_{pf} exp\left(\frac{-E_{ac}}{R_u\,(T+273.15)}\right) \tag{11}$$

Where, D_{pf} is pre-exponential factor and R_u is universal gas constant.

3.9.2. Energy and exergy analysis (EEA)

In this section, EEA of ISD including SAC and drying chamber is carried out. The equations to determine parameters studied in energy analysis of SAC and drying chamber, and exergy analysis of SAC and drying chamber are presented.

3.9.2.1. Energy analysis of ISD

In ISD, the SAC and drying chamber were assumed as steady flow devices and those were analyzed using steady flow mass and energy conservation principles. By mass conservation principle, the mass flow rate is constant which means the rate of air coming in equal to the rate of air coming out of the system [104].

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \tag{12}$$

where, $\dot{m}_a$ represents the mass flow rate of air (kg/s). The subscripts *i* and *o* represent inlet and outlet.

By energy conservation principle, rate of energy transfer by work, heat and mass into the system equal to the rate of energy transfer by work, heat and mass coming out of the system [105].

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{13}$$

$$\dot{Q} + \sum \dot{m}_{ai} \left(h_{ai} + \frac{v_{ai}^2}{2} + z_i g \right) = \sum \dot{m}_{ao} \left(h_{ao} + \frac{v_{ao}^2}{2} + z_o g \right) + \dot{W} \tag{14}$$

where, $\dot{Q}$ is the net heat transfer to the system, $\dot{W}$ is net work done by the system, h_a, v_a and z represent enthalpy, velocity and height from the datum of air. There is no work done by the dryer. The difference between kinetic and potential energies of the dryer is very small and it is neglected.

Energy analysis of solar air collector (SAC)

By applying steady flow mass and energy conservation principles to SAC, the following equations [105] were obtained from Eqs. (12) and (14).

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} = \sum \dot{m}_a \tag{15}$$

$$\dot{Q} = \dot{Q}_{u,SAC} = \dot{Q}_{in,SAC} - \dot{Q}_{ls,SAC} = \dot{m}_a \left(h_{ao} - h_{ai} \right) \tag{16}$$

where, $\dot{Q}_{u,SAC}$ is the useful heat supplied by SAC, $\dot{Q}_{in,SAC}$ is the heat input to SAC and $\dot{Q}_{ls,SAC}$ is the heat lost from SAC. $\dot{Q}_{in,SAC}$ is calculated using [92];

$$\dot{Q}_{in,SAC} = I_s A_{SAC} \quad (17)$$

where, I_s is instantaneous solar radiation (W/m^2) at a given time and A_{SAC} is the area of SAC which is calculated as 1.8 m^2.

$\dot{Q}_{u,SAC}$ [44] is calculated using;

$$\dot{Q}_{u,SAC} = \dot{m}_a\, c_{pa}(T_{co} - T_{ci}) \quad (18)$$

where, c_{pa} is the specific heat of air in (kJ/kgK), T_{co} and T_{ci} are the temperatures of air at SAC outlet and inlet.

The collector efficiency or energy efficiency of the collector ($\eta_{en,SAC}$) is the ratio of useful heat supplied by collector to the heat input to SAC and is given by [41,59];

$$\eta_{en,SAC} = \frac{\dot{Q}_{u,SAC}}{\dot{Q}_{in,SAC}} = \frac{\dot{m}_a\, c_{pa}(T_{co} - T_{ci})}{I_s A_{SAC}} \quad (19)$$

Energy analysis of the drying chamber

The drying efficiency or overall energy efficiency of the solar dryer ($\eta_{en,dry}$) [64] is the ratio of energy needed to eliminate moisture from the food product to energy input to the dryer (E_{in}). It is calculated using;

$$\eta_{en,dry} = \frac{m_w L}{E_{in}} \quad (20)$$

where, L is the latent heat of vaporization of water (kJ/kg), E_{in} is the energy input to the dryer which is equal to the total solar radiation falling on SAC and PV panels, m_w is found by difference between initial and final mass of the product after completion of drying (m_i - m_f).

E_{in} is calculated using [106];

$$E_{in} = I_s \times (A_{SAC} + A_{PV}) \times t_d \quad (21)$$

where, t_d represents total drying time of dried sample and A_{PV} represents the area of solar PV panels.

The specific energy consumption (SEC) of the solar dryer is described as the amount of energy input to the solar dryer per kg of moisture eliminated from the food slice and it is given by [59];

$$SEC = \frac{E_{in}}{m_w} \tag{22}$$

The specific moisture extraction rate (SMER) is the ratio of the amount of moisture evaporated to the total energy input to the solar dryer as it is an inversion of SEC and given by [38];

$$SMER = \frac{m_w}{E_{in}} \tag{23}$$

3.9.2.2. Exergy analysis of ISD

Exergy is the available energy that can be used in a system and it is a measure of the quality of energy. Exergy analysis of the thermal system is based on the second law of thermodynamics. It gives information about available energy that can be used to optimize the drying process in the dryer. The exergy per unit mass of any system [106] is the sum of internal energy (u), entropy (s), flow work, momentum energy, gravitational energy, chemical energy and radiation energy and it is calculated using:

$$Ex = (u - u_\infty) - T_0(s - s_\infty) + P_o(v - v_\infty) + \frac{V^2}{2} + g(z - z_\infty) + \textstyle\sum_{ch}(\mu_{ch} - \mu_\infty)N_{ch} + \sigma A_i F_i(3T^4 - T_\infty^4 - 4T_\infty T^3) \tag{24}$$

where, μ is the chemical potential (kJ/mol), N is the number of moles and F is the shape factor of the surface. The subscripts, ∞ is the reference or surrounding environmental conditions and ch is the chemical.

In general, the drying process is assumed as a steady flow process. The momentum, gravitational, chemical and radiation energies are neglected. The radiation energy is neglected due to low temperature difference between the dryer and atmosphere. The change in pressure of the system and exergy loss of product is also neglected. By applying the above assumptions, Eq. (24) becomes [107];

$$\dot{Ex} = \dot{m}_a c_{pa}\left[(T - T_0) - T_o ln\left(\frac{T}{T_0}\right)\right] \tag{25}$$

Where, T_0 is atmospheric temperature.

Exergy analysis of the SAC

Exergy balance for SAC is given by [108];

$$\sum \dot{E}x_{in,SAC} - \sum \dot{E}x_{out,SAC} = \sum \dot{E}x_{ls,SAC} \quad (26)$$

where, $\dot{E}x_{in,SAC}$, $\dot{E}x_{out,SAC}$ and $\dot{E}x_{ls,SAC}$ are exergy input, exergy output and exergy loss of SAC, respectively.

$\dot{E}x_{in,SAC}$ [105] associated with solar radiation falling on collector surface is expressed as;

$$\dot{E}x_{in,SAC} = \left[1 - \frac{T_0}{T_{sn}}\right] \dot{Q}_{in,abs} \quad (27)$$

where, T_{sn} represents the apparent sun temperature (6000 K) and $\dot{Q}_{in,abs}$ is the radiation falling on absorber plate [108].

$$\dot{Q}_{in,abs} = \alpha \tau I_s A_{SAC} \quad (28)$$

where, α is absorptivity (0.95) and τ is transmissivity of window glass (0.88) [109].

$\dot{E}x_{out,SAC}$ [106] is expressed as;

$$\dot{E}x_{out,SAC} = \dot{m}_a c_{pa} \left[(T_{co} - T_{ci}) - T_0 ln \left(\frac{T_{co}}{T_{ci}}\right)\right] \quad (29)$$

$\dot{E}x_{ls,SAC}$ [105] can be evaluated from irreversibility and it is given by;

$$\dot{E}x_{ls,SAC} = I = T_0 S_{gen} = \left[1 - \frac{T_0}{T_s}\right] \dot{Q}_{in,SAC} - \dot{m}_a c_{pa} \left[(T_{co} - T_{ci}) - T_0 ln \left(\frac{T_{co}}{T_{ci}}\right)\right] \quad (30)$$

The exergy efficiency of SAC [106,108] is obtained as;

$$\eta_{ex,SAC} = \frac{\dot{E}x_{out,SAC}}{\dot{E}x_{in,SAC}} = 1 - \frac{\dot{E}x_{ls,SAC}}{\dot{E}x_{in,SAC}} = 1 - \frac{T_0 S_{gen}}{\left[1 - \left({T_0}/{T_s}\right)\right] \dot{Q}_{in,SAC}} \quad (31)$$

Exergy analysis of the drying chamber

Exergy balance for drying chamber is expressed as follows [110];

$$\sum \dot{Ex}_{in,dc} - \sum \dot{Ex}_{out,dc} = \sum \dot{Ex}_{ls,dc} \quad (32)$$

where, $\dot{Ex}_{in,dc,}$ $\dot{Ex}_{out,dc,}$ and $\dot{Ex}_{ls,dc}$ are exergy input, exergy output and exergy loss of the drying chamber, respectively.

The exergy input and exergy output [107] of the drying chamber are determined using:

$$\dot{Ex}_{in,dc} = \dot{m}_a c_{pa} \left[(T_{dci} - T_0) - T_0 ln\left(\frac{T_{dci}}{T_0}\right) \right] \quad (33)$$

$$\dot{Ex}_{out,dc} = \dot{m}_a c_{pa} \left[(T_{dco} - T_0) - T_0 ln\left(\frac{T_{dco}}{T_0}\right) \right] \quad (34)$$

where, T_{dci} and T_{dco} are temperatures of the air at drying chamber inlet and outlet, respectively.

The exergy efficiency [105,110] of drying chamber is estimated using;

$$\eta_{ex,dc} = \frac{\dot{Ex}_{out,dc}}{\dot{Ex}_{in,dc}} 1 - \frac{\dot{Ex}_{ls,dc}}{\dot{Ex}_{in,dc}} \quad (35)$$

Exergy sustainability indicators

Exergy sustainability indicators such as improvement potential (IP), Environmental impact factor (EIF), waste exergy ratio (WER) and sustainability index (SI) address the irreversibilities and exergy losses in a process for given exergy input. The thermodynamic performance can be better evaluated through these indicators. As exergy losses are increased, IP, EIF and WER increased and SI decreased. IP gives the improvement capability of the system. EIF describes the environmental damage of the system. WER reveals the exergy loss per given unit exergy input. SI describes the lifetime of the system. These indicators give enough information about the irreversibilities, thermodynamic performance and sustainability of the dryer. By analyzing these indicators, one can easily design an optimum dryer by reducing irreversibilities in the drying process. The indicators such as IP, EIF, WER and SI are calculated from the following equations [84,111].

$$IP = \left(1 - \eta_{ex,dc}\right) \dot{Ex}_{ls,dc} \quad (36)$$

$$EIF = WER \frac{1}{\eta_{ex,dc}} \quad (37)$$

$$WER = \frac{\dot{Ex}_{ls,dc}}{\dot{Ex}_{in,dc}} \quad (38)$$

$$SI = \frac{1}{1-\eta_{ex,dc}} \quad (39)$$

These exergy sustainability parameters were estimated for the drying chamber of NCISD and FCISD without TES device, and FCISD without and with TES device and compared for exergetic assessment of the drying process.

3.9.3. Uncertainty analysis

It is necessary to determine the uncertainties while measuring independent (measured) parameters and finding dependent (estimated) parameters during the experimentation. If a dependent parameter (*R*) is given, which influenced by some of the independent parameters (x_1, x_2, x_3…, x_n), its uncertainty (w_R) was estimated using [42,59];

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (40)$$

Chapter 4

Results and discussion

Chapter 4

4. Results and discussion

4.1. Introduction

In this chapter, the drying kinetics and energy and exergy analysis of natural convection indirect solar dryer (NCISD) and forced convection ISD (FCISD) without thermal energy storage (TES) device during drying guava, muskmelon and beetroot were discussed. Next, the drying kinetics and energy and exergy analysis of FCISD without TES device (model-1) and with TES device (model-2) during drying guava, muskmelon, beetroot and green chilli were discussed. The graphs for various parameters during drying guava slices are presented to reduce the number of graphs, but the data of various parameters for remaining samples is clearly addressed.

4.2. Indirect solar dryer without TES

4.2.1. Solar radiation data

The drying experiments were conducted from March to May of 2021 and 2022. Initially, guava slices were dried in NCISD and FCISD without TES device consecutively from April 19 to April 22, 2021 at NIT Warangal (79.58° E, 18° N). Next, muskmelon slices were dried in NCISD and FCISD without TES device consecutively from May 02 to May 05, 2021. Similarly, the beetroot slices were dried in NCISD and FCISD setups consecutively from March 25 to 28, 2022. The experiments were conducted from 8.00 am to 5.00 pm with a duration of 9 h in a day. Initially, experiments were conducted on NCISD for two days. After the experiments with NCISD, the next set of experiments were conducted in FCISD for two days. The instantaneous solar radiation (I_s) of both days was noted while drying guava slices in NCISD and FCISD and mentioned in **Fig. 4.1.** In the X-axis of **Fig. 4.1**, 0.00 represents 8.00 am of the first day, 9.00 represents the 5.00 pm of the first day, 10.00 represents 8.00 am of the second day and 19.00 represents the 5.00 pm of the second day. During drying guava slices, the I_s was 282−1038 W/m^2 and 254−1006 W/m^2 on NCISD and FCISD setups, respectively. Similarly, during drying muskmelon slices, the I_s was ranged from 286 to 940 W/m^2 and 282 to 940 W/m^2 on NCISD and FCISD setups, respectively. During drying beetroot slices, the range of I_s was 254 to 978 W/m^2 and 296 to 985 W/m^2 on NCISD and FCISD setups, respectively. Since the tests were performed on successive days with similar climatic conditions, the average I_s was almost the same in both setups.

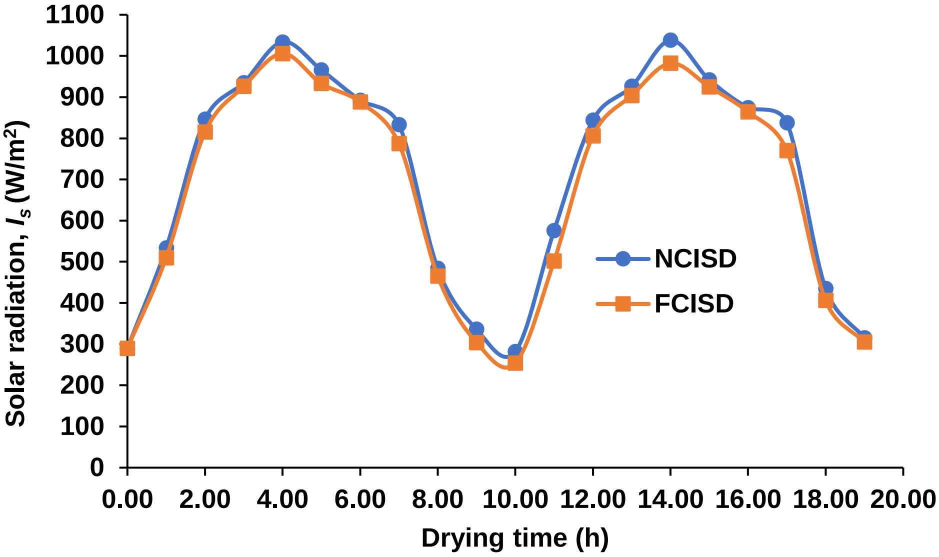


Fig. 4.1. Variation of solar radiation with time while drying guava slices

4.2.2. Temperature distribution

Let T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} be the atmosphere, trapezoidal duct exit (or inlet of SAC), the outlet of SAC, trays 1 to 4 temperatures, respectively. During drying guava slices in NCISD, these temperatures T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were measured and reported in **Fig. 4.2.** The temperature from tray-1 to tray-4 is decreased due to the food products absorb certain heat in each tray. A 32−67 °C temperature range was noticed in the drying cabinet of NCISD during drying guava slices. The maximum temperatures of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} in NCISD are 44.5, 45, 73, 67, 64, 61 and 59 °C, respectively. The averages are 39, 39.65, 57.45, 52.95, 50.85, 48.75 and 47.15 °C, respectively.

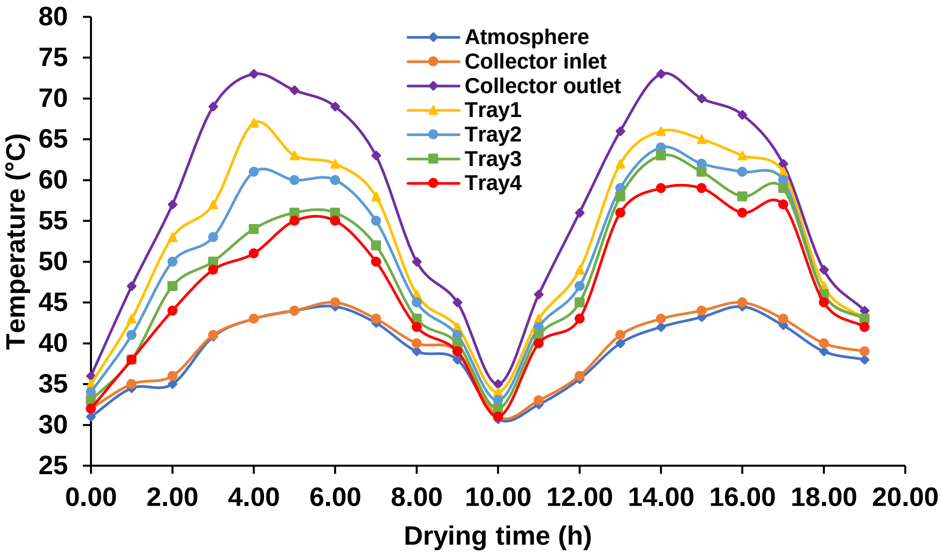


Fig. 4.2. Temperature measurements at various locations in NCISD while drying guava slices

The temperature data collected in the FCISD setup during drying guava slices is presented in **Fig. 4.3.** The drying chamber temperature (T_{dc}) in FCISD was ranged from 29 to 59 °C. The average temperatures of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were 38.24, 38.85, 52.55, 47.50, 45.95, 44.25 and 42.85 °C, respectively. From **Figs. 4.2** and **4.3**, it is observed that the average T_{co} of NCISD and FCISD are 330.06 and 325.7 K, average temperature of drying chamber (T_{dc}) of NCISD and FCISD are 323.07 and 318.28 K. The above temperatures are low in FCISD setup compared to NCISD setup because the enhanced air velocity diminishes the stay time of hot air inside the FCISD setup. Also, the FCISD setup draws more fresh air as the air velocity is enhanced.

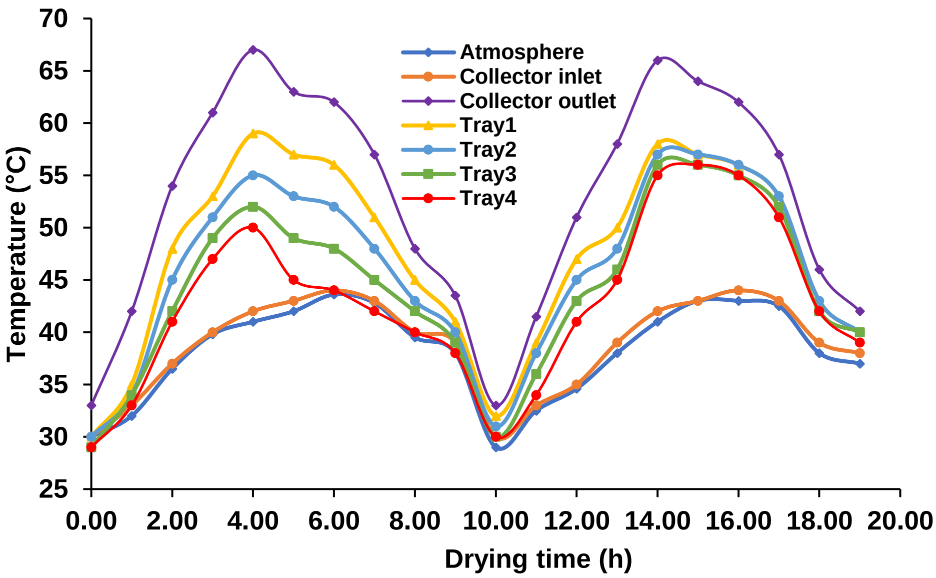


Fig. 4.3. Temperature measurements at various locations in FCISD while drying guava slices

Similarly, while drying muskmelon slices, the average temperatures of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} in NCISD were 37.02, 37.5, 54.57, 50.2, 47.55, 45.4 and 43.65 °C, respectively. Whereas in FCISD, the averages were 36.63, 37.05, 51.2, 46, 43.75, 41.85 and 40.15 °C, respectively. During drying muskmelon slices, the average T_{co} of NCISD and FCISD are 327.73 and 324.35 K. Also, the average T_{dc} of NCISD and FCISD are 319.85 and 316.09 K. Similarly, while drying beetroot slices, the average values of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were 37.78, 38.1, 56.97, 51.25, 48.65, 46.15 and 44.35 °C, respectively. Whereas in FCISD, the averages were 37.41, 38.07, 53.22, 48.15, 46.3, 44.7 and 43.05 °C, respectively. During drying beetroot slices, the average T_{dc} was 320.75 and 318.70 K in NCISD and FCISD, respectively.

4.2.3. Drying kinetics

4.2.3.1. Moisture content (MC)

The average initial moisture contents (MCs) of guava, muskmelon, beetroot and green chilli were found to be 5.5355, 12.4156, 7.7535 and 8.3985 kg/kg of dry basis (db), respectively (already reported in **Table 3.3, 3.4, 3.5 and 3.6**). The variation of MC of guava slices in trays−1 to 4 in NCISD and OSD methods is shown in **Fig. 4.4**. It is observed that MC of guava slices increased from tray-1 to tray-4 as tray-1 is exposed to higher drying air temperature so the products in tray-1 lose a higher amount of MC than other trays. At each tray, the MC decreases with time as it loses the MC and follows a falling rate period. On the first day, most of the MC is lost since unbound moisture is eliminated. The final MC of guava slices in NCISD on trays−1 to 4 were 0.0130, 0.0195, 0.0260 and 0.0391 db, respectively. The guava slices dried in OSD reached a final MC of 0.4574 db.

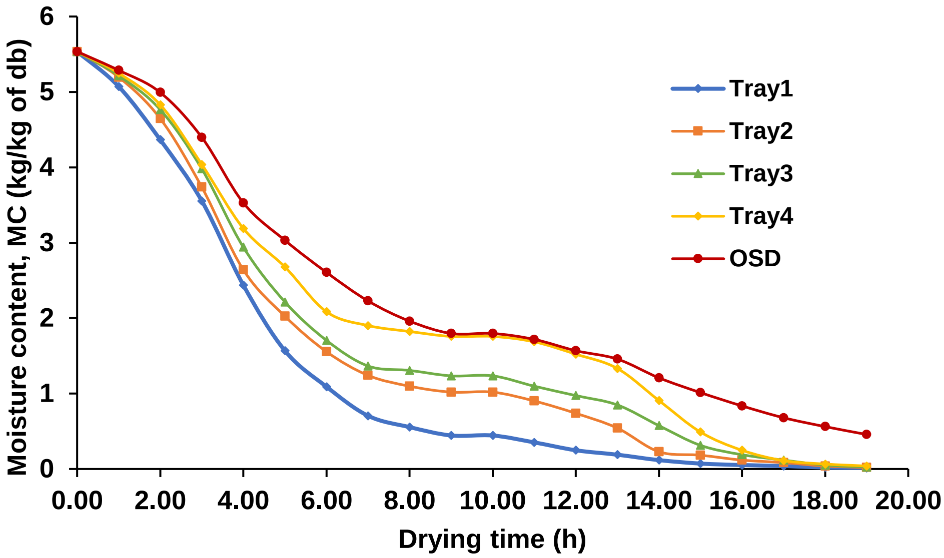


Fig. 4.4. Moisture content variation of guava slices in NCISD

Figure 4.5 mentions the MC of guava slices in trays-1 to 4 in FCISD and OSD method. The MC with time variation is almost similar in both FCISD and NCISD but the time to reach the final MC of guava slices is decreased. This is due to the velocity increment in FCISD. The drying time saved was 4 hours in FCISD and the final MC of guava slices reached 14 h in FCISD.

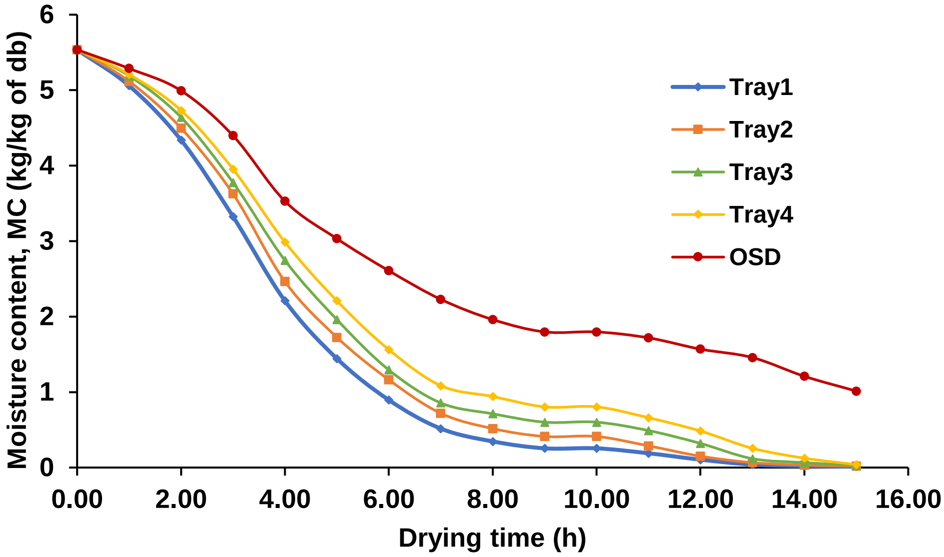


Fig. 4.5. Moisture content variation of guava slices in FCISD

Similarly, the MC of muskmelon slices is decreased with time, and also a falling rate period is noticed. The final MC of muskmelon slices in NCISD was 0.1269, 0.1537, 0.1672 and 0.1939 db on trays−1 to 4, respectively. In the OSD method, it was 0.4355 db at a similar duration of 18 h. Similar experiments were performed with the FCISD dryer and final MC is reached by 15 h in FCSID compared to 18 h in NCISD. Similarly, during drying beetroot slices, the average MCs of trays−1, 2, 3 and 4 and OSD were 2.4655, 2.6156, 3.0446, 3.2050 and 3.8936 db and the final MCs were 0.0242, 0.0329, 0.0504, 0.1204 and 0.75945 db, respectively. The variation in MC of beetroot slices with time in FCISD is similar to NCISD and the final MC is achieved in 15 h in FCISD.

4.2.3.2. Samples dried in ISD and OSD

Figure 4.6 gives the real picture of the final dried guava slices in ISD (either in forced or natural convection) and OSD methods. The average final MC of guava slices was 0.0244 db and it is reached by 14, 18 and 24 h in FCISD, NCISD and OSD methods, respectively. It is observed that OSD products look dusty due to the open environment. Color degradation is also observed in OSD products due to direct exposure to the sun and higher drying duration. The higher drying time increases the browning reactions which degrade the colour in guava slices [26,112]. The browning reactions promote the oxidation of phenolic compounds and therefore, the total phenolic compound (TPC) value becomes lower in products dried in OSD compared to ISD. The dimensional change of dried guava slices was not significant in ISD and OSD methods.

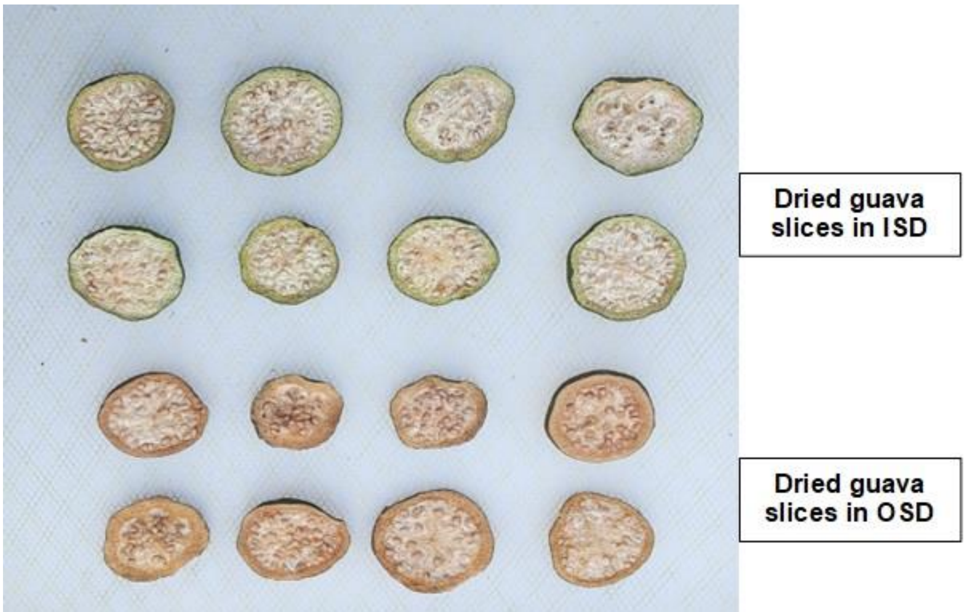


Fig. 4.6. Snapshot of dried guava slices in ISD and OSD

The dried muskmelon slices in ISD and OSD were reported in **Fig. 4.7.** The slices took the time of 15, 18 and 22 h in FCSID, NCISD and OSD techniques, respectively to reach the average final MC of 0.1605 db. It is noticed that more dust on the products which was dried in OSD method as the products were exposed in direct sun and open environment. Also, slight colour degradation was noticed in OSD dried products as shown in **Fig. 4.7.**

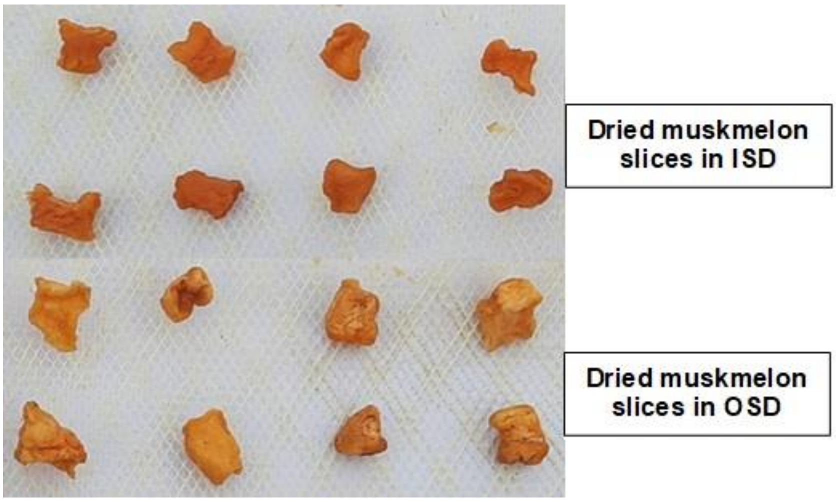


Fig. 4.7. Snapshot of dried muskmelon slices

While drying beetroot slices, the average final MC of 0.05699 db was reached in 15, 18 and 26 h in FCISD, NCISD and OSD, respectively. The dried beetroot slices in ISD and OSD was shown in **Fig. 4.8.** The colour of dried beetroot slices is faded more in OSD due to direct exposure of sunlight. The decrease in colour of beetroot indicates reduction of betalain pigment which is crucial for antiviral and antibacterial activity [21]. Also, the OSD dried slab surfaces had dust. ISD dried slabs are clean and there is not much colour degradation which concluded that high quality beetroot slices were produced in ISD compared to OSD.

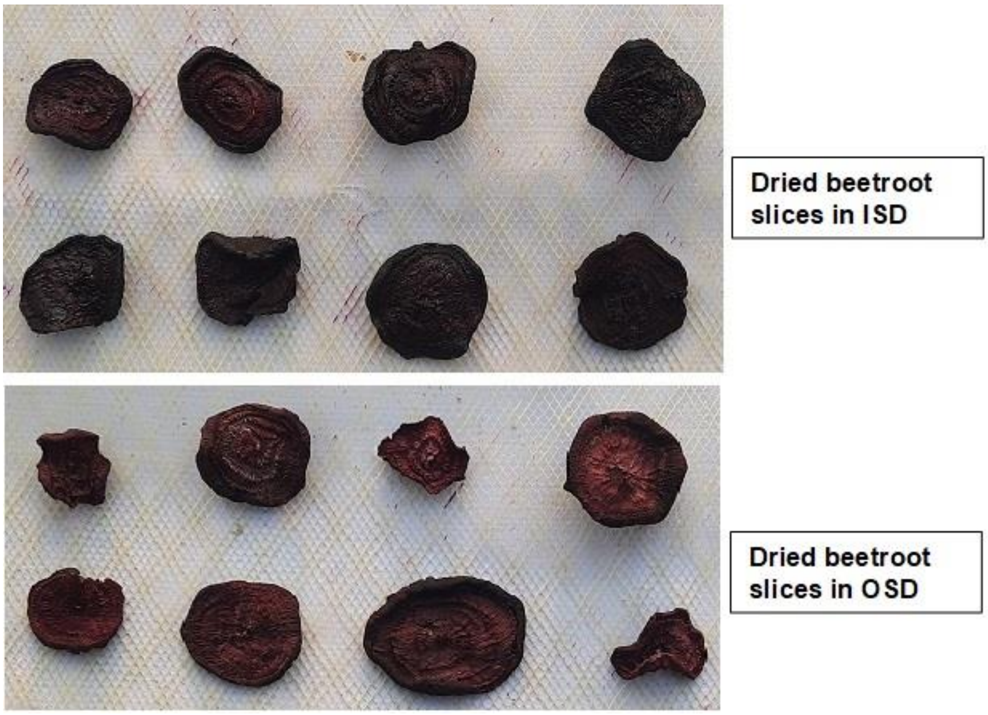


Fig. 4.8. Snapshot of dried beetroot slices

4.2.3.3. Drying rate (DR)

The DR of guava slices in NCISD and FCISD is shown in **Fig. 4.9.** The DRs are high at initial hours due to the quick removal of bound moisture from the guava slices in both ISDs. In FCISD, the drying rates are high compared to NCISD since more amount of air enters inside the cabinet and takes higher MC from the guava slices. The maximum DR of guava slices was observed as 1.0261 and 1.0702 kg/h in NCISD and FCISD, respectively. The average DR of guava slices was 0.3062 and 0.3936 kg/h in NCISD and FCISD dryers which was an increase of 28.54% in FCISD compared to NCISD.

Similarly, the DR of muskmelon slices was determined for both NCISD and FCISD dryers. The maximum DR of muskmelon slices was noticed as 2.0727 and 2.1197 kg/h in NCISD and FCISD, respectively. The average DR of muskmelon slices was 0.6808 and 0.817 kg/h in NCISD and FCISD dryers which was an increase of 20.01% in IFCSD. Similarly, the average DR of beetroot slices was found to be 0.4276 and 0.5131 kg/h in NCISD and FCISD, respectively. The increment in average DR of beetroot slices was 19.99% in FCISD due to enhanced air velocity compared to NCISD.

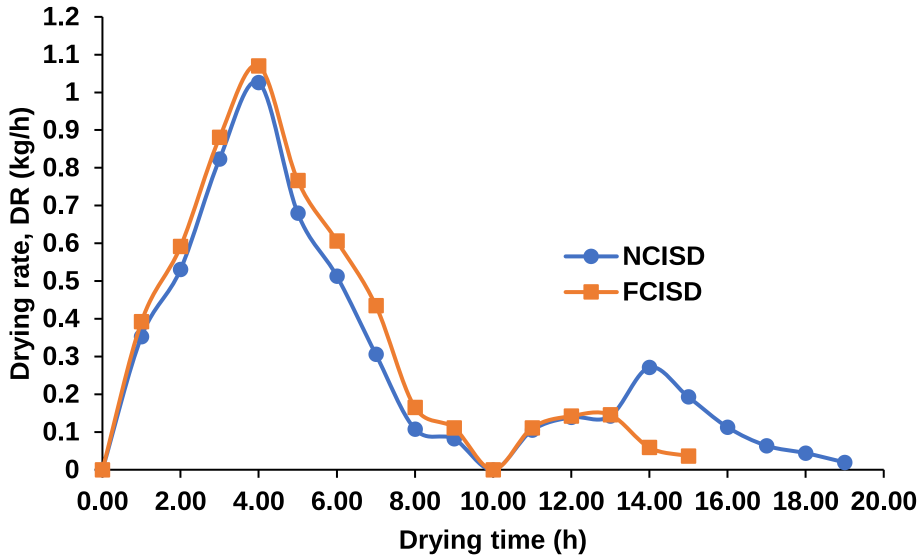


Fig. 4.9. Drying rate of guava slices in NCISD and FCISD

4.2.3.4. Moisture ratio (MR)

The MC of guava slices is normalized by a non-dimensional parameter such as moisture ratio (MR). In the present study, twelve empirical models which represent the MR in terms of drying time were chosen from existing studies (**Table 3.7**). The drying characters of guava slices on the four trays in NCISD, FCISD and OSD are evaluated for all twelve models. The best six models to describe drying characters of guava slices in NCISD and FCISD were reported with their R^2 and χ^2 values in **Table 4.1.** and **Table 4.2.** The Two-term exponential, Page model and Verma models were the best drying models to define the drying kinetics of guava slices due to higher values of R^2= 0.99565, 0.99789, 0.98528 and lower values of χ^2 = 0.00047, 0.00026, 0.00125 in NCISD, FCISD and OSD, respectively. Verma and Page models served the next two best models to describe drying kinetics of guava slices in NCISD as they produced the next best values of R^2 and χ^2. Verma and Two-term exponential models served the next two best models to describe drying kinetics of guava slices in FCISD. The fitting of the best model with experimental data of guava slices for NCISD and FCISD is shown in **Fig. 4.10.**

Table 4.1. Regression results of best six models for guava slices in NCISD

Model name	**Tray no**	**constants**	R^2	χ^2

Two-term exponential	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.36665; a = 2.10834 k = 0.27355; a = 1.91995 k = 0.23524; a = 1.83927 k = 0.17120; a = 1.63096 k = 0.14366; a = 1.584	0.99565 0.98419 0.97554 0.96182 0.97961	0.00047 0.00164 0.00248 0.00365 0.00173

Verma model	Tray 1
	
	Tray 2
	
	Tray 3
	
	Tray 4
	
	OSD
		k = 0.39004; a = 2.5842;
		g = 0.67962
		k = 0.22659; a = 1.26777;
		g = 1.63098
		k = 0.19666; a = 1.21532;
		g = 1.76424
		k = 0.2004; a = 12.45725;
		g = 2.0863
		k = 0.12704; a = 1.10151;
		g = 2.62144
			0.99545
			
			0.98822
			
			0.98098
			
			0.95959
			
			0.98528
				0.00049
				
				0.00122
				
				0.00193
				
				0.00386
				
				0.00125

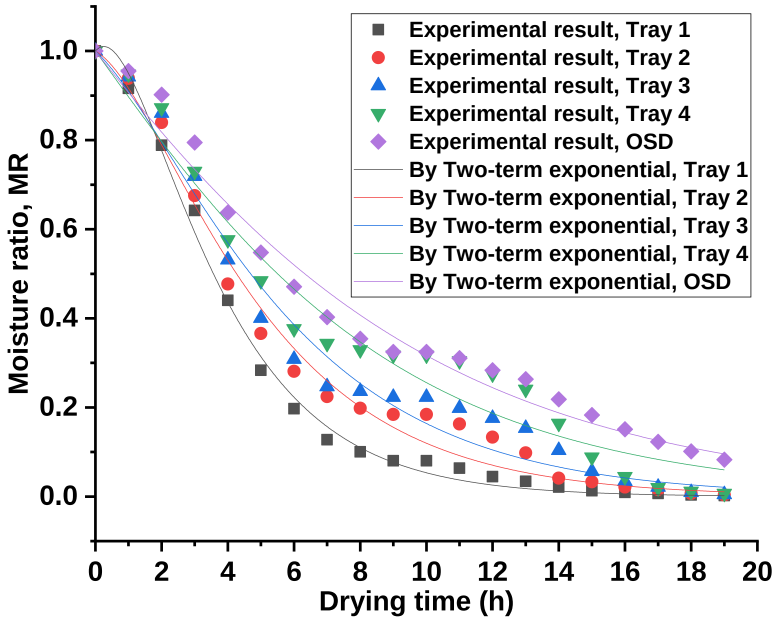
Page model	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.08805; n =1.5344 k = 0.11462; n = 1.24938 k = 0.11033; n = 1.19994 k = 0.10096; n = 1.13115 k = 0.0909; n = 1.10337	0.99395 0.98215 0.97493 0.96282 0.98093	0.00065 0.00185 0.00255 0.00355 0.00162
Modified Page	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.2158; n = 1.58197 k = 0.17666; n = 1.24791 k = 0.15931; n = 1.19811 k = 0.13171; n = 1.13151 k = 0.11379; n = 1.10256	0.99395 0.98215 0.97493 0.96282 0.98093	0.00065 0.00185 0.00255 0.00355 0.00162
Logarithmic	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.2252; a = 1.13595 c = -0.03576 k = 0.18162; a = 1.1105 c = -0.03127 k = 0.16312; a = 1.10348 c = -0.03012 k = 0.11293; a = 1.13032 c = -0.10135 k = 0.1221; a = 1.05463 c = 0.00268	0.97327 0.97806 0.97265 0.96445 0.98144	0.00289 0.00227 0.00278 0.00340 0.00157
Henderson and Pabis	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.24738; a = 1.11382 k = 0.1975; a = 1.0924 k = 0.17644; a = 1.0855 k = 0.14175; a = 1.05899 k = 0.12135; a = 1.05343	0.97143 0.97779 0.97315 0.96202 0.98247	0.00309 0.0023 0.00273 0.00363 0.00149

Table 4.2. Regression results of best six models for guava slices in FCISD

Model name	**Tray no**	**constants**	R^2	χ^2
Page model	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.07960; n =1.73318 k = 0.07428; n = 1.67522 k = 0.07366; n = 1.59990 k = 0.07547; n = 1.49986 k = 0.09248; n = 1.09372	0.99789 0.99597 0.99155 0.98898 0.97293	0.00026 0.00050 0.00104 0.00131 0.00205

Modified Page	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.23222; n = 1.73079 k = 0.21183; n = 1.67406 k = 0.19587; n = 1.59821 k = 0.17859; n = 1.49727 k = 0.11339; n = 1.0924	0.99789 0.99597 0.99155 0.98898 0.97293	0.00026 0.00050 0.00104 0.00131 0.00205
Verma model	Tray 1	k = 0.54414; a = 49.26408; g = 0.55749	0.99703	0.00037
	Tray 2	k = 0.48912; a = 31.71056; g = 0.50771	0.99653	0.00043
	Tray 3	k = 0.35206; a = 2.42591; g = 0.66207	0.99431	0.00070
	Tray 4	k = 0.28357; a = 1.77444; g = 0.75864	0.99299	0.00083
	OSD	k = 0.12556; a = 1.09329; g = 74.79921	0.97889	0.00160
Two-term exponential	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.40489; a = 2.16112 k = 0.36735; a = 2.15032 k = 0.33802; a = 2.13959 k = 0.30276; a = 2.09673 k = 0.14073; a = 1.55578	0.99609 0.99607 0.99468 0.99332 0.97102	0.00048 0.00049 0.00065 0.00079 0.00220
Wang and Singh	Tray 1 Tray 2 Tray 3 Tray 4 OSD	a = -0.17236; b = 0.00727 a = -0.16014; b = 0.00638 a = -0.14955; b = 0.00567 a = -0.1377; b = 0.00488 a = -0.10196; b = 0.0033	0.97685 0.97714 0.97314 0.97364 0.97458	0.00286 0.00284 0.00330 0.00313 0.00193
Logarithmic	Tray 1	k = 0.22528; a = 1.17737 c = -0.07775	0.96882	0.00385
	Tray 2	k = 0.19859; a = 1.19329 c = -0.09488	0.97061	0.00365
	Tray 3	k = 0.18144; a = 1.1987 c = -0.10007	0.96991	0.00369
	Tray 4	k = 0.16109; a = 1.20442 c = -0.11318	0.97275	0.00324
	OSD	k = 0.13979; a = 0.99597 c = 0.07211	0.97585	0.00183

(a)



(b)

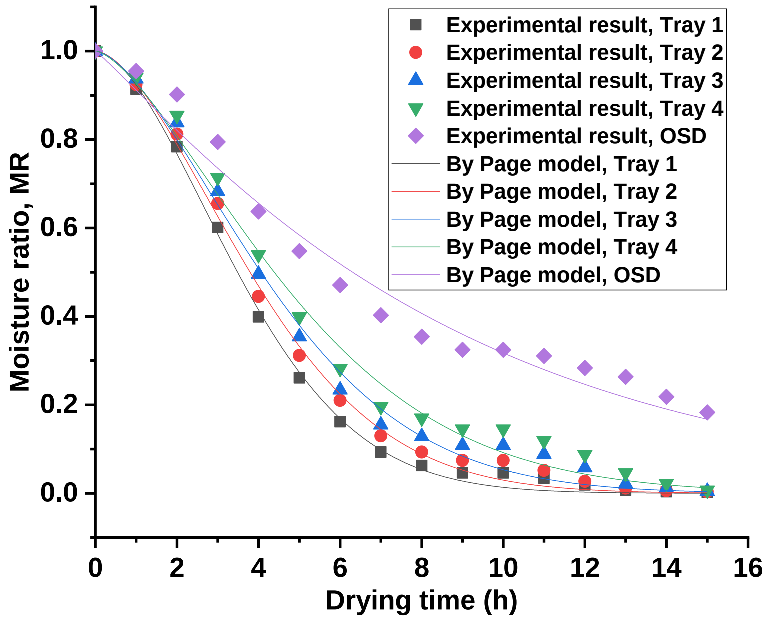


Fig. 4.10. Drying curves fitted with best model while drying guava slices in (a) NCISD and (b) FCISD

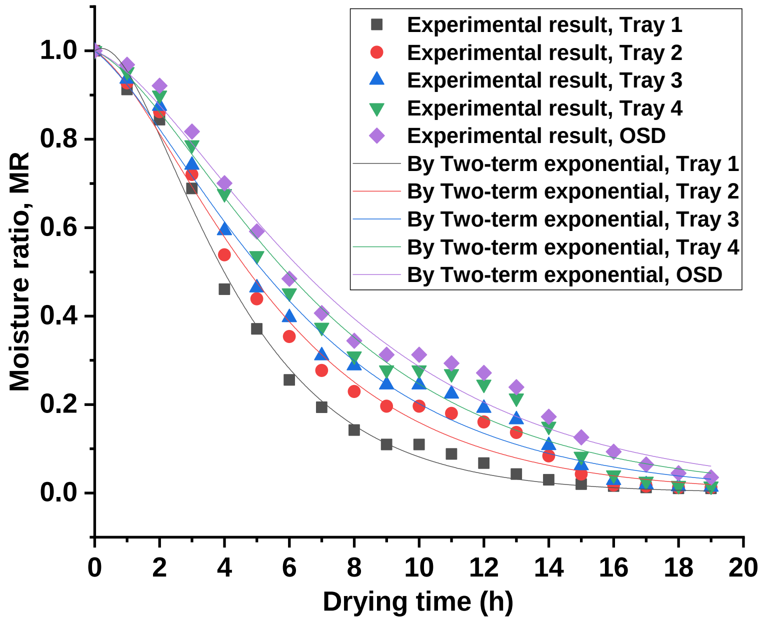
Similarly, the drying characters of muskmelon slices on the four trays in NCISD, FCISD and OSD are evaluated for all twelve models. From 12 relations, the top fitted six relations in FCISD with R^2 and χ^2 numerals are presented in **Table 4.3** (NCISD results were not shown here). The Two-term exponential, Two-term exponential and Verma models were the best drying models to define the drying kinetics of muskmelon slices due to its maximums of R^2 = 0.99505, 0.99544, 0.98752 and minimums of χ^2 = 0.00054, 0.00052, 0.00114 in NCISD, FCISD and OSD, respectively. The next best two models to describe drying kinetics of muskmelon slices in NCISD and FCISD were; Verma and Page models since they have the next better R^2 and χ^2. The experimental data of muskmelon slices were fitted with the Two-term exponential model for NCISD, FCISD and OSD as represented in **Fig. 4.11.**

Table 4.3. Model fitting results for muskmelon slices in FCISD

Model name	**Tray no**	**constants**	R^2	χ^2
Two term exponential	Tray 1	a = 2.0665; k = 0.35892	**0.99544**	**0.00052**
	Tray 2	a = 2.09625; k= 0.32293	0.99555	0.00053
	Tray 3	a = 2.08544; k= 0.30345	0.99578	0.00049
	Tray 4	a = 2.0768; k = 0.28199	0.99718	0.00033
	OSD	a = 1.89086; k= 0.17662	0.98215	0.00163
Verma model	Tray 1	a = 2.81821; k = 0.39078 g = 0.62307	0.99520	0.00055
	Tray 2	a = 3.43422; k = 0.3657 g = 0.53394	0.99543	0.00054
	Tray 3	a = 2.03701; k = 0.30099 g = 0.64547	0.99549	0.00053
	Tray 4	a = 2.14331; k = 0.28494 g = 0.57141	0.99698	0.00035
	OSD	a = 1.22142; k = 0.14292 g = 1.18927	0.98752	0.00114
Page model	Tray 1	k = 0.09663; n =1.51977	0.99430	0.00065
	Tray 2	k = 0.07527; n = 1.56103	0.99417	0.00069
	Tray 3	k = 0.07473; n = 1.51257	0.99304	0.00082
	Tray 4	k = 0.06786; n = 1.50730	0.99497	0.00059
	OSD	k = 0.06403; n = 1.27598	0.98093	0.00174
Modified Page	Tray 1	k = 0.21492; n = 1.51672	0.99430	0.00065
	Tray 2	k = 0.19072; n = 1.55973	0.99417	0.00069
	Tray 3	k = 0.18001; n = 1.51052	0.99304	0.00082
	Tray 4	k = 0.16784; n = 1.50426	0.99497	0.00059
	OSD	k = 0.11602; n = 1.2746	0.98093	0.00174
Wang and Singh	Tray 1	a = -0.1589; b = 0.00626	0.97932	0.00237
	Tray 2	a = -0.1453; b = 0.00533	0.97953	0.00243
	Tray 3	a = -0.1383; b = 0.00488	0.97920	0.00244
	Tray 4	a = -0.1294; b = 0.00428	0.98200	0.00211
	OSD	a = -0.0923; b = 0.00233	0.97293	0.00248
Logarithmic	Tray 1	k = 0.21154; a = 1.14562 c = -0.0607	0.97571	0.00278
	Tray 2	k = 0.1788; a = 1.18137 c = -0.0907	0.97429	0.00305
	Tray 3	k = 0.16688; a = 1.18709 c = -0.0967	0.97594	0.00283
	Tray 4	k = 0.14759; a = 1.2154 c = -0.1286	0.97986	0.00237
	OSD	k = 0.10282; a = 1.18874	0.97658	0.00214

		c = -0.1171		

(a)



(b)

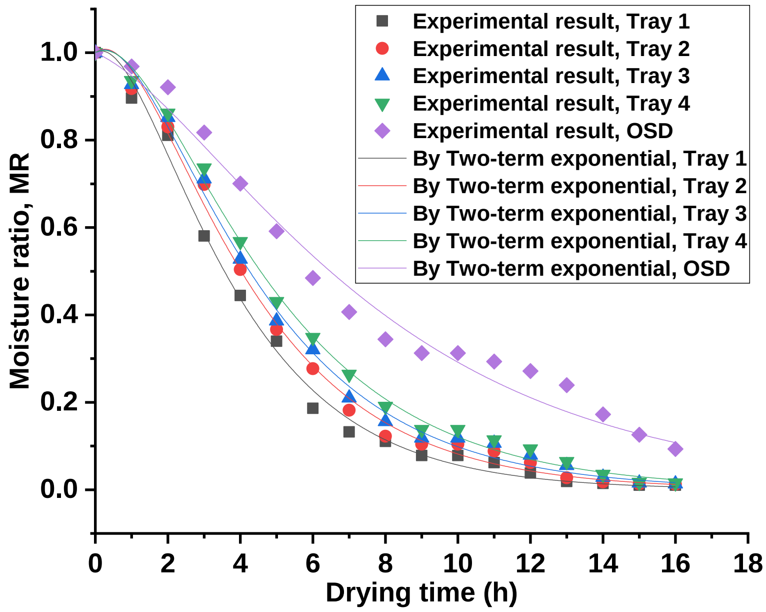


Fig. 4.11. Drying curves fitted with best model while drying muskmelon slices in (a) NCISD and (b) FCISD

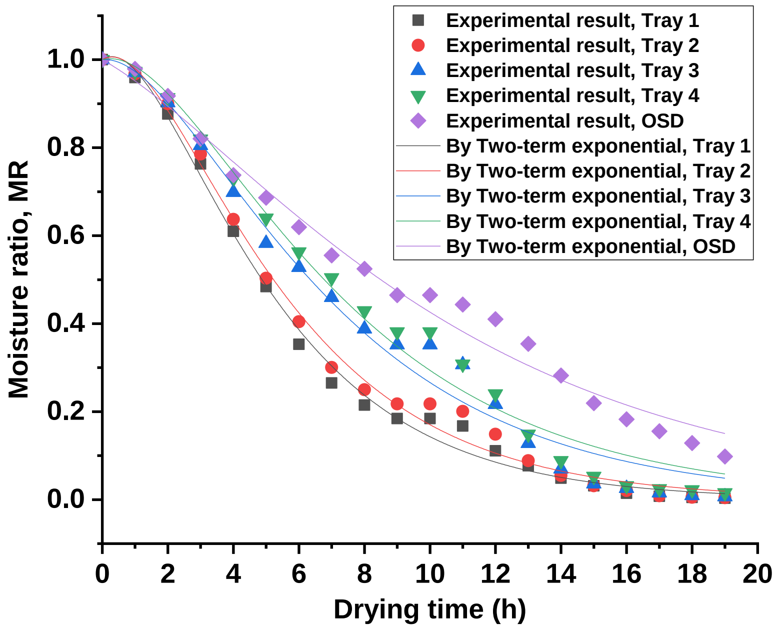
Similarly, the drying characters of beetroot slices on the four trays in NCISD, FCISD and OSD are evaluated for all twelve models. From 12 relations, the top fitted six relations in FCISD with R^2 and χ^2 numerals are presented in **Table 4.4** (NCISD results were not shown here). The Two-term exponential model was the best drying model to define the drying kinetics of beetroot slices due to its higher values of R^2 = 0.99488, 0.99650, 0.98382 and lower values of χ^2 = 0.00060, 0.00043, 0.00106 in NCISD, FCISD and OSD, respectively. The experimental data of beetroot slices were fitted with the Two-term exponential model for NCISD, FCISD and OSD as represented in **Fig. 4.12.**

Table 4.4. Regression results of beetroot slices in FCISD

Model name	**Tray no**	**constants**	R^2	χ^2
Two-term exponential	Tray 1	k = 0.3022; a = 2.1132	**0.99650**	**0.00043**
	Tray 2	k = 0.27234; a= 2.1247	0.99594	0.00050
	Tray 3	k = 0.2553; a= 2.1173	0.99411	0.00072
	Tray 4	k = 0.22697; a = 2.0948	0.99051	0.00113
	OSD	k = 0.11933; a= 1.74815	0.98382	0.00106
Verma model	Tray 1	k = 0.32361; a = 2.66887; g = 0.55175	0.99633	0.00045
	Tray 2	k = 0.35705; a = 22.22707; g = 0.37596	0.99614	0.00048
	Tray 3	k = 0.27675; a = 2.81142; g = 0.45631	0.99378	0.00076
	Tray 4	k = 0.29892; a = 32.43377; g = 0.30922	0.99062	0.00111
	OSD	k = 0.14656; a = 17.12116; g = 0.15229	0.98274	0.00113
Page model	Tray 1	k = 0.06728; n = 1.55682	0.99446	0.00068
	Tray 2	k = 0.05316; n = 1.59164	0.99508	0.00061
	Tray 3	k = 0.05108; n = 1.56139	0.99213	0.00096
	Tray 4	k = 0.04226; n = 1.57328	0.99117	0.00105
	OSD	k = 0.0516; n = 1.20544	0.98455	0.00101
Modified Page	Tray 1	k = 0.17666; n = 1.55366	0.99446	0.00068
	Tray 2	k = 0.15825; n = 1.58963	0.99508	0.00061
	Tray 3	k = 0.14884; n = 1.55959	0.99213	0.00096
	Tray 4	k = 0.13385; n = 1.57297	0.99117	0.00105
	OSD	k = 0.08552; n = 1.20574	0.98455	0.00101
Wang and Singh	Tray 1	a = -0.13443; b = 0.00454	0.98011	0.00243
	Tray 2	a = -0.11961; b = 0.00353	0.98054	0.00241
	Tray 3	a = -0.11137; b = 0.00302	0.97837	0.00264
	Tray 4	a = -0.09631; b = 0.00205	0.98162	0.00218
	OSD	a = -0.06488; b = 0.00097	0.98525	0.00097
Logarithmic	Tray 1	k = 0.15537; a = 1.22549; c = -0.13203	0.97873	0.00259
	Tray 2	k = 0.12416; a = 1.30314; c = -0.21258	0.98123	0.00233
	Tray 3	k = 0.11145; a = 1.33634; c = -0.24798	0.98097	0.00232
	Tray 4	k = 0.08139; a = 1.49977; c = -0.42657	0.98478	0.00181
	OSD		0.98573	0.00093

		k = 0.04983; a = 1.47081; c = -0.44856		

(a)



(b)

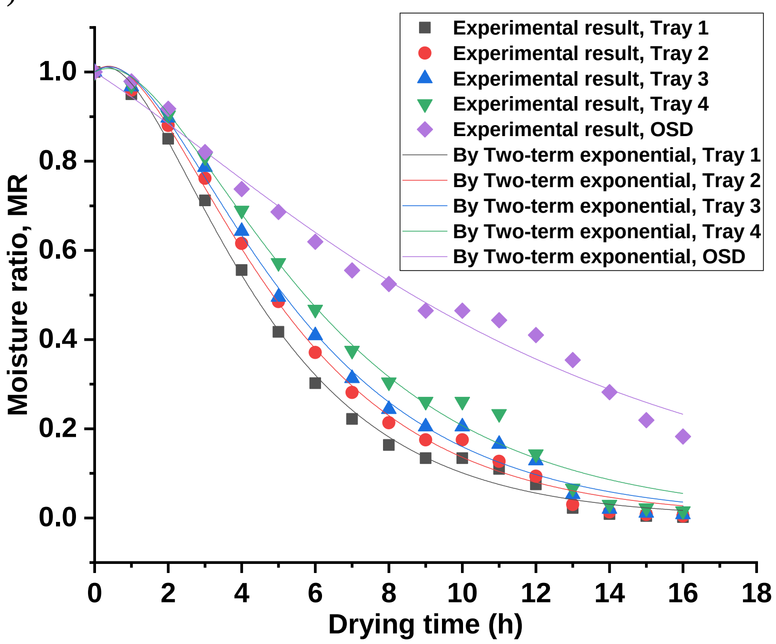


Fig. 4.12. Drying curves fitted with best model while drying beetroot slices in (a) NCISD and (b) FCISD

4.2.3.5. Effective diffusion coefficient (D_{ef})

The thermal properties such as effective diffusion coefficient (D_{ef}), mass and heat transfer coefficients (h_{mt} and h_{ht}) and activation energy (E_{ac}) were estimated during guava, muskmelon and beetroot slices in NCISD and FCISD. The average values of D_{ef}, h_{mt} and h_{ht} were found out for the same duration in NCISD and FCISD for comparison during drying guava, muskmelon and beetroot. The D_{ef} increases with drying time as the moisture is continuously removed from the beetroot slices. During drying guava slices, the D_{ef} is plotted in **Fig. 4.13** for NCISD and FCISD setups. The D_{ef} varied from 2.29×10^{-9} to 1.09×10^{-8} m^2/s and 2.29×10^{-9} to 1.76×10^{-8} m^2/s, for the same duration of 14 h in NCISD and FCISD, respectively. The average D_{ef} for 14 hours in NCISD was 5.95×10^{-9} m^2/s, whereas, in FCISD, it was 7.98×10^{-9} m^2/s, which is a 34.12% increase. The D_{ef} is higher in FCISD which enables higher MC movement within the food product.

Similarly for muskmelon slices, the D_{ef} varied from 9.14×10^{-9} to 5.04×10^{-8} m^2/s and 2.29×10^{-9} to 5.81×10^{-8} m^2/s, for the same duration of 15 h in NCISD and FCISD, respectively. The average D_{ef} of muskmelon slices in NCISD was 2.45×10^{-8} m^2/s, in FCISD, it was 3.04×10^{-8} m^2/s, which is a 24.08% enhancement. Similarly, for beetroot slices, the D_{ef} varied from 2.29×10^{-9} to 1.29×10^{-8} m^2/s and 2.29×10^{-9} to 1.62×10^{-8} m^2/s, for the same duration of 15 h in NCISD and FCISD, respectively. The average D_{ef} of beetroot slices is improved by 20.3% in FCISD compared to NCISD, which was 5.9×10^{-9} and 7.11×10^{-9} m^2/s in NCISD and FCISD, respectively. The calculated D_{ef} values were in a similar range which is available in the literature. Wang et al. [38] found the D_{ef} of mango slices and these were ranged between 6.41×10^{-11} and 1.18×10^{-10} m^2/s. Essalhi et al. [100] found D_{ef} of grapes and it was from 2.34×10^{-11} to 4.08×10^{-11} m^2/s. Mahapatra and Tripathy [73] found D_{ef} of carrot slices and it was between $2.59-6.36 \times 10^{-8}$ m^2/s. Lingayat al. [92] found that the D_{ef} of apple pieces was in the range of 2.29×10^{-9} to 6.02×10^{-9} m^2/s.

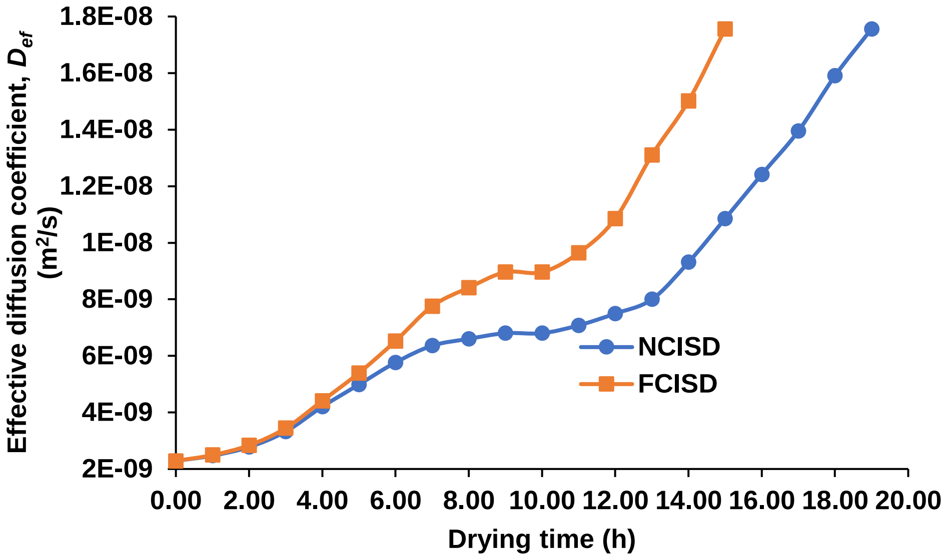


Fig. 4.13. Change in D_{ef} of guava slices with time in NCISD and FCISD

4.2.3.6. Mass and heat transfer coefficients (h_{mt} and h_{ht})

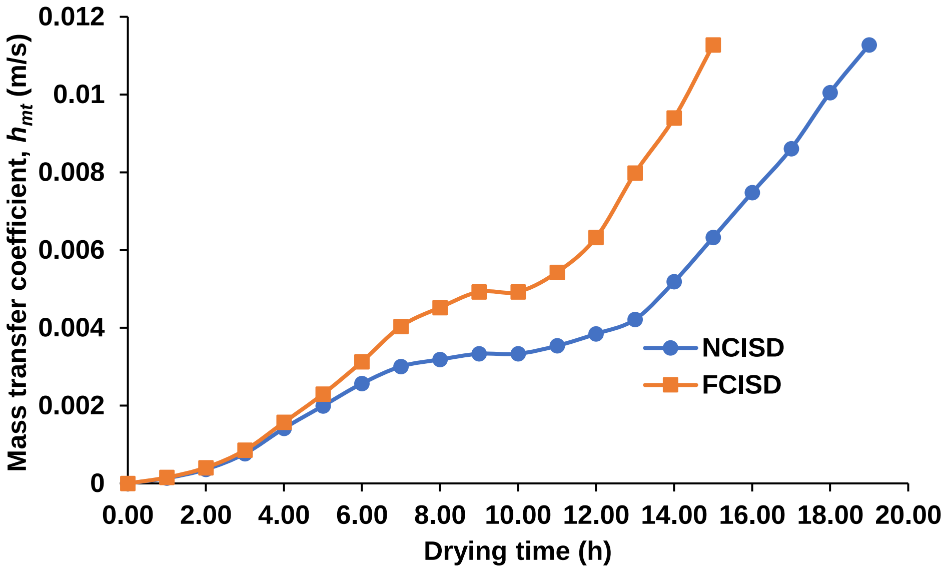
The h_{mt} and h_{ht} values are inter-related and the variation of these values for guava slices with drying time are plotted in **Fig. 4.14.** The h_{mt} values of guava slices were in the range of 0.137 to 6.32 × 10^{-3} m/s and 0.153 to 11.28 × 10^{-3} m/s in NCISD and FCISD, respectively at a duration of 14 hours. The average h_{mt} of guava slices in NCISD was 2.70 ×10^{-3} m/s, whereas, in FCISD, it was 4.20 × 10^{-3} m/s, which is a 55.55% increase. The h_{ht} values of guava slices were 0.16 to 7.29 W/m^2K and 0.18 to 12.99 W/m^2K in NCISD and FCISD, respectively. The average increment of 55.59% was noticed on the h_{ht} value of guava slices in FCISD compared to NCISD. The average h_{ht} of guava slices was 3.112 and 4.842 W/m^2K in NCISD and FCISD, respectively.

Similarly, the values of h_{mt} of muskmelon slices were from 0.162–8.46 × 10^{-3} m/s and 0.194–10.04 × 10^{-3} m/s in NCISD and FCISD, respectively. The average h_{mt} of muskmelon in NCISD is 2.81 × 10^{-3} m/s, in FCISD, it is 4.36 × 10^{-3} m/s and it is a 55.16% enhancement. The range of h_{ht} of muskmelon slices was 0.19–9.75 W/m^2K and 0.22–11.57 W/m^2K in NCISD and FCISD, respectively. The average h_{ht} of muskmelon slices was 3.235 and 5.026 W/m^2K in NCISD and FCISD, respectively. It was an increment of 55.36% in FCISD compared to NCISD.

Similarly, the values of h_{mt} of beetroot slices are in the range of 6.8 × 10^{-5} to 7.85 × 10^{-3} m/s and 8.11 × 10^{-5} to 10.22 × 10^{-3} m/s for the duration of 15 h in NCISD and FCISD, respectively.

The average h_{mt} of beetroot slices in NCISD was 2.67 × 10^{-3} m/s and in FCISD, it was 3.56 × 10^{-3} m/s with an improvement of 33.33%. The h_{ht} values of beetroot slices were from 0.078 to 9.037 W/m^2K and 0.093 to 11.773 W/m^2K in NCISD and FCISD, respectively. The average increment of h_{ht} of beetroot slices was 33.17% in FCISD compared to NCISD which was 3.081 and 4.103 W/m^2K in NCISD and FCISD, respectively. The estimated h_{mt} and h_{ht} are in a similar range available in the literature. The h_{mt} values of cocoa beans were reported by Koua et al. [103] and it was ranged between 1.88 × 10^{-7} and 7.88 × 10^{-5} m/s. Das and Akpinar [113] reported h_{mt} values of 0 to 0.007 m/s for pear slices drying. Ndukwu et al. [114] obtained the h_{ht} of potato slices and it was 0.64 to 10.5 W/m^2K. Lemus-Mondaca et al. [115] obtained the average h_{ht} of papaya slices and it was ranged from 0.25 to 4.55 W/m^2K. for papaya slices.

(a)



(b)

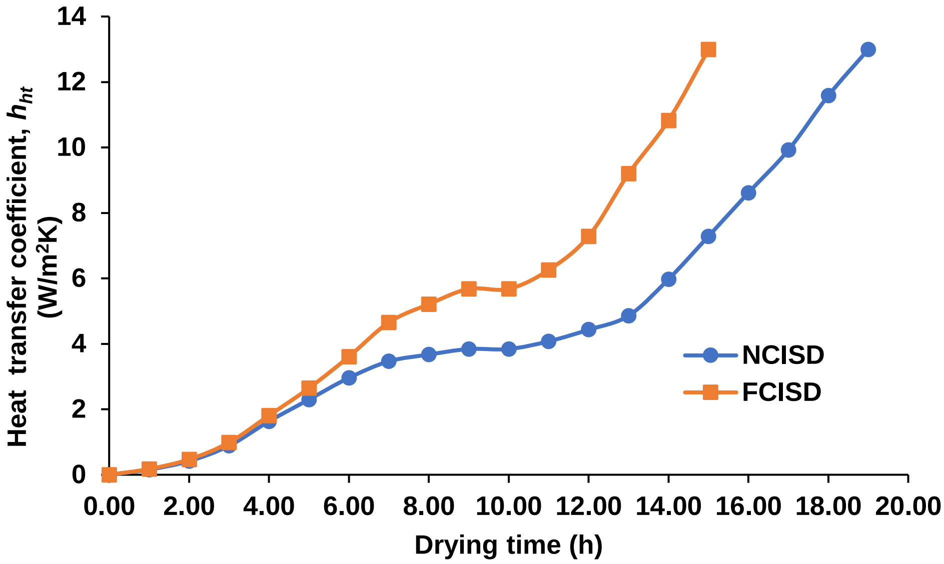


Fig. 4.14. Variation of (a) h_{mt} and (b) h_{ht} of guava slices with time

4.2.3.7. Activation energy (E_{ac})

The E_{ac} was found by plotting a curve between (ln D_{ef}) and (1/T+273) at each time and finding the best linear curve fitting with the highest value of R^2. The E_{ac} of guava slices is estimated to be 136.98 kJ/mol in NCISD, whereas in FCISD, it is 116.49 kJ/mol, which is an almost 14.96% decrease. The E_{ac} of muskmelon slices is 38.06 and 28.61 kJ/mol in NCISD and FCISD, which is a 24.83% decrease. The E_{ac} of beetroot slices was estimated to be 27.57 and 23.22 kJ/mol in NCISD and FCISD, respectively. There is a decrement of E_{ac} (15.78%) in FCISD compared to NCISD. Increased velocity of air in FCISD results in lowering the amount of energy required to remove MC from food products. A similar value of E_{ac} was found in guava slices (88.47 to 122.68 kJ/mol [116]), carrot pieces (36.63 to 45.63 kJ/mol [73]), ivy gourd (28.46 to 45.20 kJ/mol [117]) and beetroot slices (24.32 kJ/mol [69]).

4.2.4. Energy and exergy analysis

4.2.4.1. Energy analysis

Useful heat supplied by collector ($\dot{Q}_{u,SAC}$)

The useful heat supplied by SAC ($\dot{Q}_{u,SAC}$) is calculated in NCISD and FCISD setups during drying guava, muskmelon and beetroot slices. The variation in $\dot{Q}_{u,SAC}$ with time in NCISD and FCISD during drying guava slices is shown in **Fig. 4.15**. As the intensity of solar radiation increases, Q_u also increases since the solar radiation is directly proportional to $\dot{Q}_{u,SAC}$. During drying guava slices, the $\dot{Q}_{u,SAC}$ range was from 172.86 to 1296.45 W in NCISD and 217.08 to 1809 W in FCISD. The increased mass flow rate in FCISD creates higher $\dot{Q}_{u,SAC}$. While drying guava slices, the average $\dot{Q}_{u,SAC}$ in NCISD was 769.23 W whereas, in FCISD, it was 991.32 W, which was a 28.8% increase. Similarly, while drying muskmelon slices, the $\dot{Q}_{u,SAC}$ was in the range of 176.88−1326.60 W in NCISD and 208.04−1733.63 W in FCISD. The average $\dot{Q}_{u,SAC}$ in NCISD and FCISD was 755.06 and 981.23 W, which was a 29.96% enhancement in FCISD. During drying beetroot slices, the variation of $\dot{Q}_{u,SAC}$ in NCISD was from 180.9 to 1401.98 W (average of 853.39 W) and in FCISD, it was from 189.95 to 1779.86 W (average of 1065.45 W), respectively. The average increment of 24.85% is observed in $\dot{Q}_{u,SAC}$ in FCISD compared to NCISD.

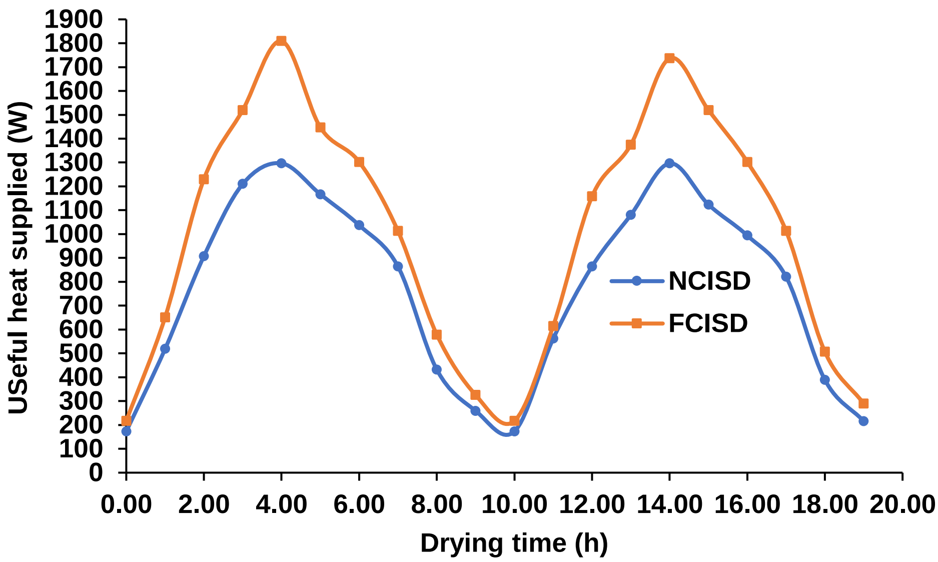


Fig. 4.15. Variation of $\dot{Q}_{u,SAC}$ with time during drying guava slices in NCISD and FCISD

Collector efficiency ($\eta_{en,SAC}$)

The $\eta_{en,SAC}$ is estimated in NCISD and FCISD setups during drying guava, muskmelon and beetroot slices. The variation of $\eta_{en,SAC}$ with time was drawn in **Fig. 4.16** during drying guava slices. It looks like that the same observation which is plotted for $\dot{Q}_{u,SAC}$ in **Fig. 4.15.** Every day, $\eta_{en,SAC}$ increases till noon and decreases at 5.00 pm as it is also proportional to the amount of $\eta_{en,SAC}$. While drying guava slices, the $\eta_{en,SAC}$ is ranged from 33.11 to 69.65% (average of 56.05%) and 36.16 to 86.87% (average of 65.37%) in NCISD and FCISD, respectively. The forced convection gives a higher velocity of the air and it dominates the $\dot{Q}_{u,SAC}$ so that $\eta_{en,SAC}$ is higher in forced convection. It is observed that there is a 16.63% increment of average $\eta_{en,SAC}$ in FCISD compared to NCISD. Similarly, during drying muskmelon slices, the range of $\eta_{en,SAC}$ was 33.42−78.4% (average of 58.50%) and 35.64−89.09% (average of 66.37%) in NCISD and FCISD, respectively. The average value of $\eta_{en,SAC}$ is increased by 13.45% in FCISD compared to NCISD during drying muskmelon slices. Similarly, during drying beetroot slices, the range of $\eta_{en,SAC}$ was from 33.72−79.32% and 36.12−87.91% in NCISD and FCISD, respectively. In NCISD, the average $\eta_{en,SAC}$ was 65.62%, whereas in FCISD, it was 71.09% with an improvement of 8.34% during drying beetroot. According to the literature, the estimated $\eta_{en,SAC}$ values were within a similar range from 12−66% in FCISD [59] and 30−88% in greenhouse dryer integrated with SAC [118].

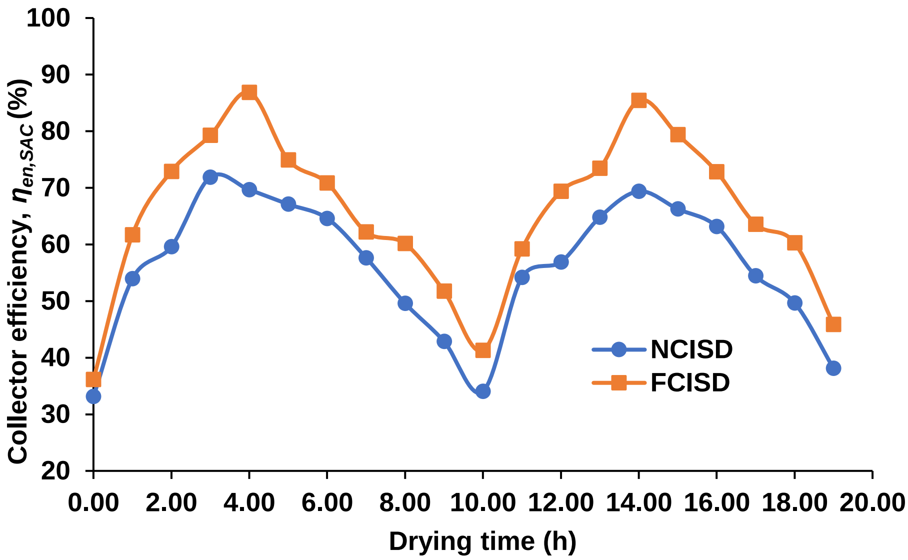


Fig. 4.16. Change in $\eta_{en,SAC}$ with time in NCISD and FCISD during drying guava slices

Drying efficiency ($\eta_{en,dry}$)

The $\eta_{en,dry}$ for NCISD and FCISD was estimated during drying guava, muskmelon and beetroot. Its variation with time is shown in **Fig. 4.17** during drying guava slices. The $\eta_{en,dry}$ values are higher on the 1st day compared to the 2nd because most of the moisture in the form of unbound is lost on the 1st day. The increased velocity of air in FCISD enables the removal of more MC from the guava slices compared to NCISD. During drying guava slices, the average $\eta_{en,dry}$ is 7.71 and 10.26% in NCISD and FCISD, respectively. The average increment of $\eta_{en,dry}$ was 33.07% in FCISD because of more MC removal from the guava slices. Similarly, during muskmelon slices, the average $\eta_{en,dry}$ in NCISD was 9.39% whereas, in FCISD, it was 11.37%, which was a 21.09% increase. Similarly, during beetroots slices, the average $\eta_{en,dry}$ in NCISD was 9.49% whereas, in FCISD, it was 11.31%, which was a 19.18% increase. It is found that estimated average $\eta_{en,dry}$ in present study is better compared with findings of 5.75% while drying banana in FCISD [119] and 4.05% while drying ginger in FCISD [120].

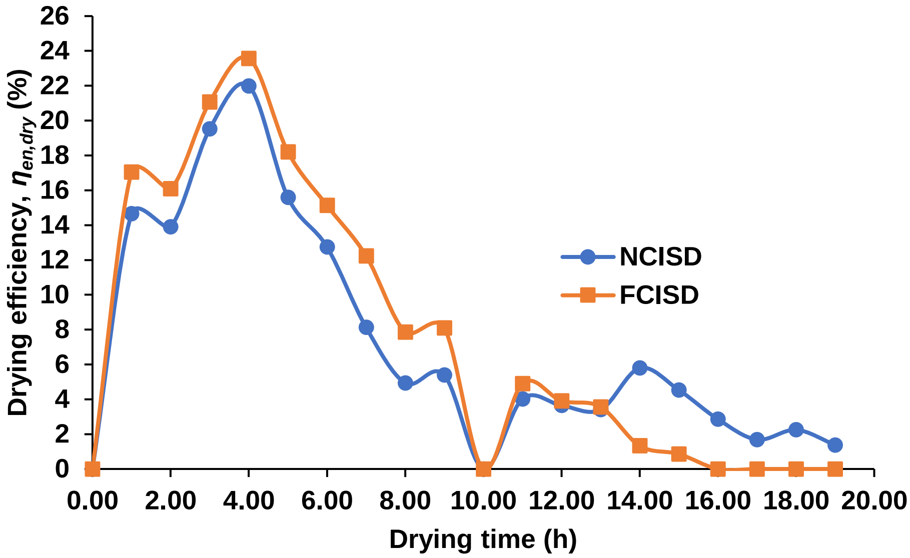


Fig. 4.17. The variation of $\eta_{en,dry}$ with time in NCISD and FCISD while drying guava slices

Specific energy consumption (SEC)

The SEC is the energy needed to eliminate one kg of water vapor from the given food product. During drying guava slices, it is noticed that SEC was 2.108 and 1.675 kWh/kg in NCISD and FCISD, respectively. A decrement of 20.54% SEC is noticed in FCISD compared to NCISD due to the lower amount of energy needed in FCISD as air velocity enhances the moisture transfer. Similarly, while drying muskmelon slices, the SEC was found to be 1.838 and 1.612 kWh/kg in NCISD and FCISD, which is a 12.30% decrease. Similarly, during drying beetroot slices, the SEC was found to be 1.947 and 1.706 kWh/kg in NCISD and FCISD, which is a 12.38% decrease. The estimated SEC of the present setup was better than the value calculated by Kesavan et al. [59] of 5.60 kWh/kg while drying banana slices in FCISD and Atalay [121] of 1.889 kWh/kg during drying orange slices in FCISD.

Specific moisture extraction rate (SMER)

The SMER is the quantity of moisture eliminated per unit quantity of energy supplied. The SMER is a reciprocal of SEC and it is higher in FCISD compared to NCISD because the increased air velocity removes more moisture from the moist materials for the given amount of energy supplied. During drying guava slices, the SMER was found to be 0.474 and 0.597 kg/kWh in NCISD and FCISD, which is a 25.95% increase. Similarly, while drying muskmelon slices, the SMER was observed to be 0.544 and 0.620 kg/kWh in NCISD and FCISD, which is a 13.97% increase. Similarly, while drying beetroot slices, the SMER was observed to be 0.514 and 0.586 kg/kWh in NCISD and FCISD, which is a 14.23% increase. The values obtained for SMER in the present study were better than the values obtained by Rabha et al. [120] of 0.113 kg/kWh during drying of ginger in FCISD and Ndukwu et al. [122] of 0.233 kg/kWh while drying plantain slices in FCISD.

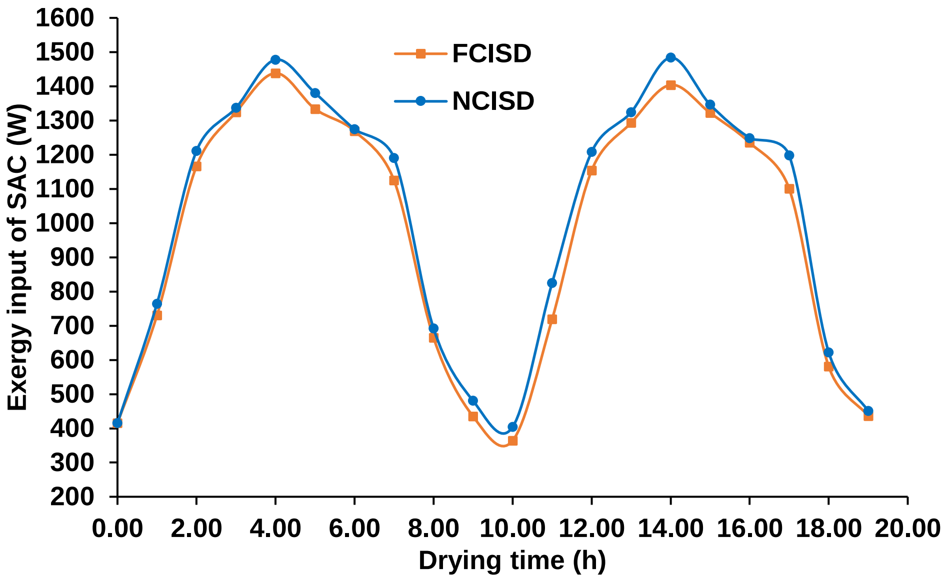
4.2.4.2. Exergy analysis

Exergy input, output and loss of the SAC

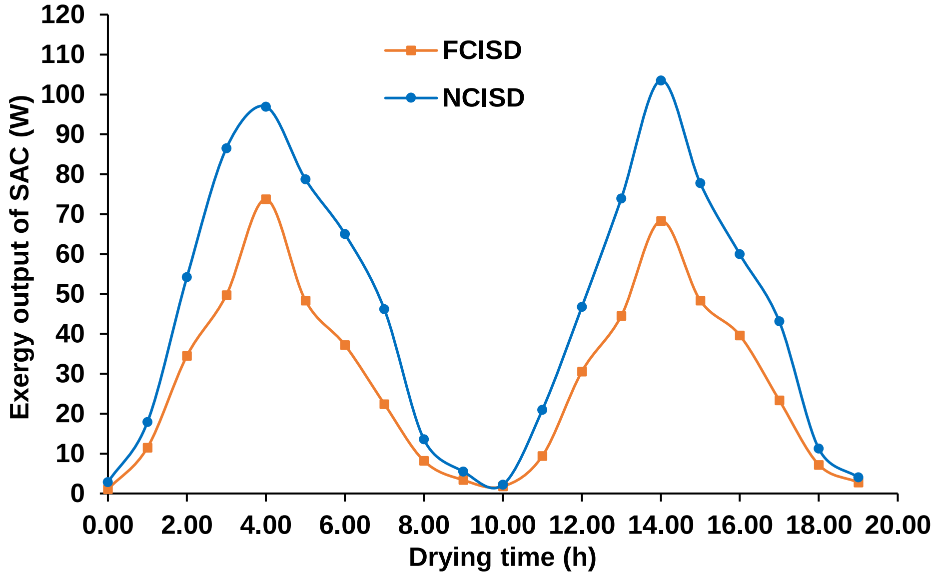
The exergy results (exergy input, output and loss) of SAC during drying guava, muskmelon and beetroot slices were determined in NCISD and FCISD, and exergy results of SAC during drying guava were shown in **Fig. 4.18.** The exergy input of SAC ($\dot{E}x_{in,SAC}$) increases till noon and then decreases (**Fig. 4.18 a**) because it is directly proportional to solar radiation and calculated with a reference to the temperature of the sun. During drying guava slices, the $\dot{E}x_{in,SAC}$ was in the range of 415.4−1483.88 W and 415.82−1438.40 W, in NCISD and FCISD, respectively. The exergy output of SAC ($\dot{E}x_{out,SAC}$) was from 2.82 to 103.52 W and 1.07 to 73.73 W in NCISD and FCISD, respectively (**Fig. 4.18 b**). Since collector temperature is higher in natural convection due to the lower airflow rate, the $\dot{E}x_{out,SAC}$ is also higher in NCISD compared to FCISD. The exergy loss of SAC ($\dot{E}x_{ls,SAC}$) was determined by the exergy balance and it is equal to the difference in exergy input and output of the SAC. In NCISD, the $\dot{E}x_{ls,SAC}$ is noticed from 412.58−1380.36 W, whereas in FCISD it is from 414.41−1364.67 W during drying guava slices (**Fig. 4.18 c**).

Similarly, while drying muskmelon slices, the $\dot{E}x_{in,SAC}$ was from 409.9 to 1344.15 W in NCISD and 375.5 to 1344.28 W in FCISD. The $\dot{E}x_{out,SAC}$ was from 2.73 to 96.63 W in NCISD and 1.03 to 65.75 W in FCISD. In FCISD, the $\dot{E}x_{ls,SAC}$ was in the range of 373.80−1278.52 W, whereas in NCISD it was 407.17−1247.52 W. Similarly, while drying beetroot slices, the average $\dot{Ex}_{in,SAC}$ was observed to be 979.73 W and 974.78 W in NCISD and FCISD, respectively. The average $\dot{Ex}_{out,SAC}$ was observed to be 47.98 W and 32.07 W in NCISD and FCISD, respectively. The average $\dot{Ex}_{ls,SAC}$ was noticed to be 931.75 W and 942.71 W in NCISD and FCISD, respectively.

(a)



(b)



(c)

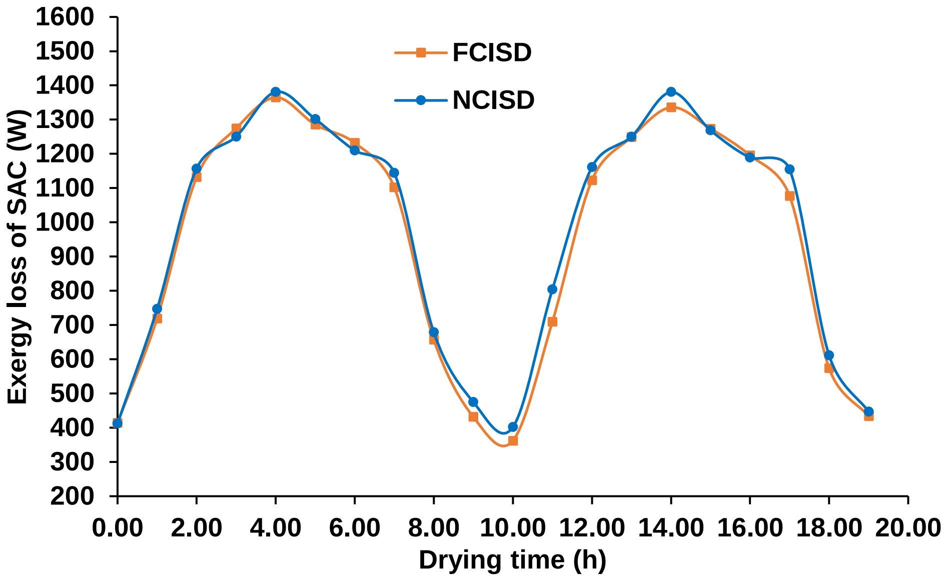


Fig. 4.18. (a) Exergy input, (b) exergy output and (c) exergy loss of SAC in ISD during drying guava slices

Exergy efficiency of the SAC ($\eta_{ex,SAC}$)

The $\eta_{ex,SAC}$ is determined in NCISD and FCISD during drying guava, muskmelon and beetroot slices and its variation with drying time is mentioned in **Fig. 4.19.** It is already observed that $\dot{E}x_{in,SAC}$ is almost the same in both dryers, so $\eta_{ex,SAC}$ is directly dependent on the $\dot{E}x_{out,SAC}$, which depends on the temperature of the SAC outlet. During drying guava slices, in NCISD, the average $\eta_{ex,SAC}$ is 3.73%, whereas in FCISD, it is 2.39% with a decrease of 35.92%. Similarly, during drying muskmelon slices the average decrement of $\eta_{ex,SAC}$ was 29.77% in FCISD compared to NCISD which was 3.46 and 2.43% in NCISD and FCISD, respectively. Similarly, during drying muskmelon slices, the average decrement of $\eta_{ex,SAC}$ was 33.49% in FCISD compared to NCISD which was 4.21 and 2.80% in NCISD and FCISD, respectively. The average $\eta_{ex,SAC}$ is noticed to be 2.28% in the ISD developed by Sethi et al. [47] and 0.81% by Bhardwaj et al. [65] which is almost the same as the present study.

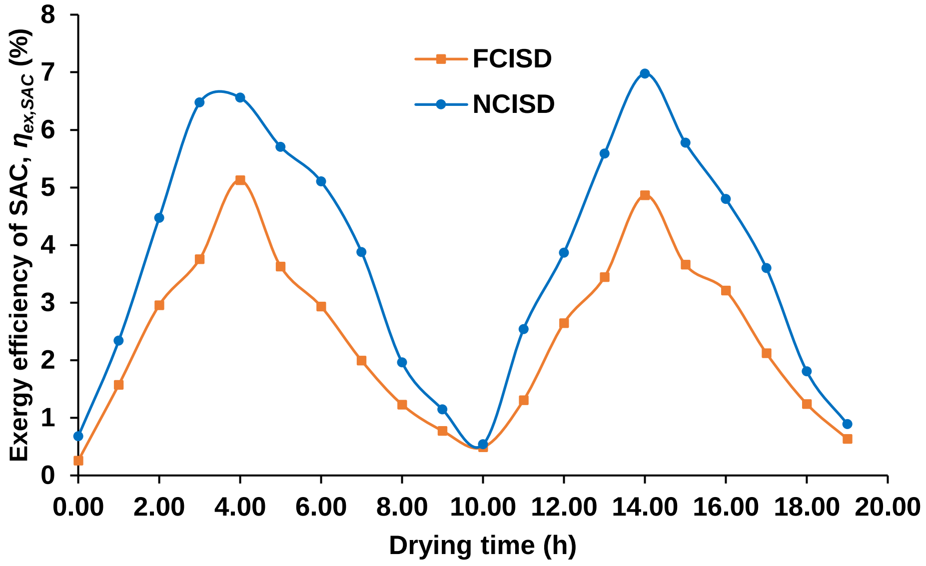
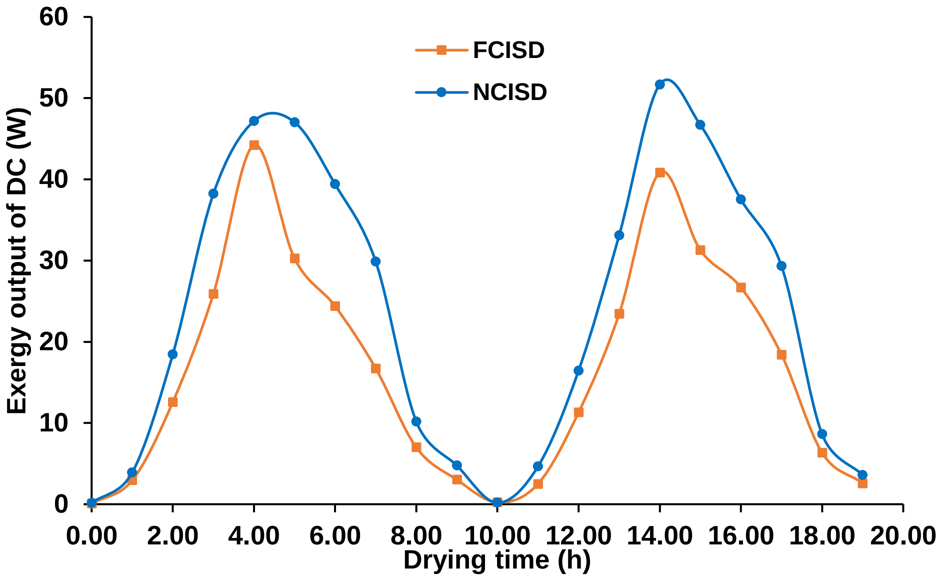


Fig. 4.19. Exergy efficiency of SAC with drying time in ISD during drying guava

Exergy input, output and loss of the drying chamber

The exergy results of drying chamber were determined in NCISD and FCISD during drying guava, muskmelon and beetroot slices. The exergy input of the drying chamber ($\dot{E}x_{in,dc}$) is equal to the $\dot{E}x_{out,SAC}$ which is shown in **Fig. 4.18 (a).** The exergy output ($\dot{E}x_{out,dc}$) and exergy loss of drying cabinet ($\dot{E}x_{ls,dc}$) with time during drying guava slices are mentioned in **Fig. 4.20 (a).** Let, T_{dci} and T_{dco} are the temperatures of the inlet and outlet of the drying chamber, respectively. The $\dot{E}x_{out,dc}$ depends on T_{dco} and the mass flow rate of air. The values of $\dot{E}x_{out,dc}$ and $\dot{E}x_{ls,dc}$ are higher in natural convection compared to forced convection since temperatures of drying chamber dominate mass flow rate of air in both setups (**Fig. 4.20**). The $\dot{E}x_{ls,dc}$ is higher in NCISD due to a higher value of ($T_{dci} - T_{dco}$) with a decreased mass flow rate of air. During drying guava slices, in NCISD, the average values of $\dot{E}x_{out,dc}$ and $\dot{E}x_{ls,dc}$ were 23.55 and 21.98 W, whereas, in FCISD, the same were 16.54 and 11.76 W, respectively. Similarly, during drying muskmelon slices, the same were 18.47 and 20.70 W in NCISD and 16.17 and 11.50 W in FCISD. Similarly, during drying beetroot slices, the same were 24.99 and 22.98 W in NCISD and 18.66 and 13.41 W in FCISD.

(a)



(b)

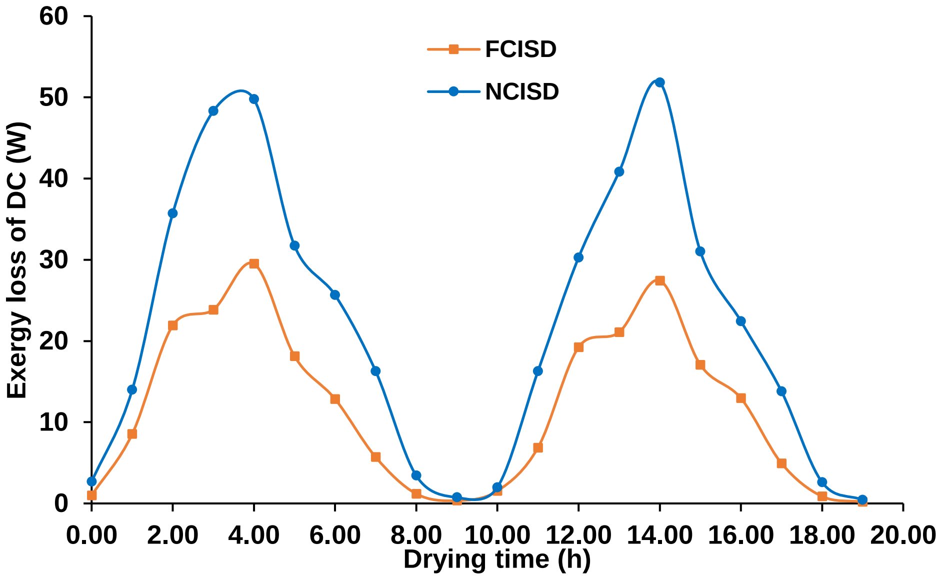


Fig. 4.20. Exergy (a) output and (b) loss of drying chamber with drying time in ISD during drying guava slices

Exergy Efficiency of drying chamber ($\eta_{ex,dc}$)

The change of $\eta_{ex,dc}$ with drying time in NCISD and FCISD is calculated during drying guava, muskmelon and beetroot slices. The variation of $\eta_{ex,dc}$ with time during drying guava slices is shown in **Fig. 4.21**. As the drying progresses, the ($T_{dci} - T_{dco}$) decreases because the amount of moisture lost is decreased. At the end of the drying period, T_{dco} approaches T_{dci} and the value of $\eta_{ex,dc}$ becomes almost 100%. It is concluded that as time increases, $\eta_{ex,dc}$ also increases (**Fig. 4.21**). It is noticed that higher values of $\eta_{ex,dc}$ are observed in FCISD compared to NCISD since the lower value of ($T_{dci} - T_{dco}$) in FCISD due to enhanced mass flow rate of air. In the NCISD, the value of $\eta_{ex,dc}$ is 5.67−89.59%, whereas, in FCISD, it is 7.21−93.23%. During drying guava slices, the average $\eta_{ex,dc}$ was found to be 50.92 and 57.03% in NCISD and FCISD, which is a 11.99% increase. Similarly, while drying muskmelon slices, the average $\eta_{ex,dc}$ was found to be 45.87 and 55.73% in NCISD and FCISD, which is a 21.50% increase. Similarly, during drying beetroot slices, the average $\eta_{ex,dc}$ was found to be 49.43 and 54.92% in NCISD and FCISD, which is a 11.11% increase. The studies from literature reported similar range of $\eta_{ex,dc}$ values in various solar dryers: bitter gourd (28.74−40.68%) [64], plantain (5.6−95.13%) [122], ginger (4−94%) [120] and potato (0−93.3%) [47].

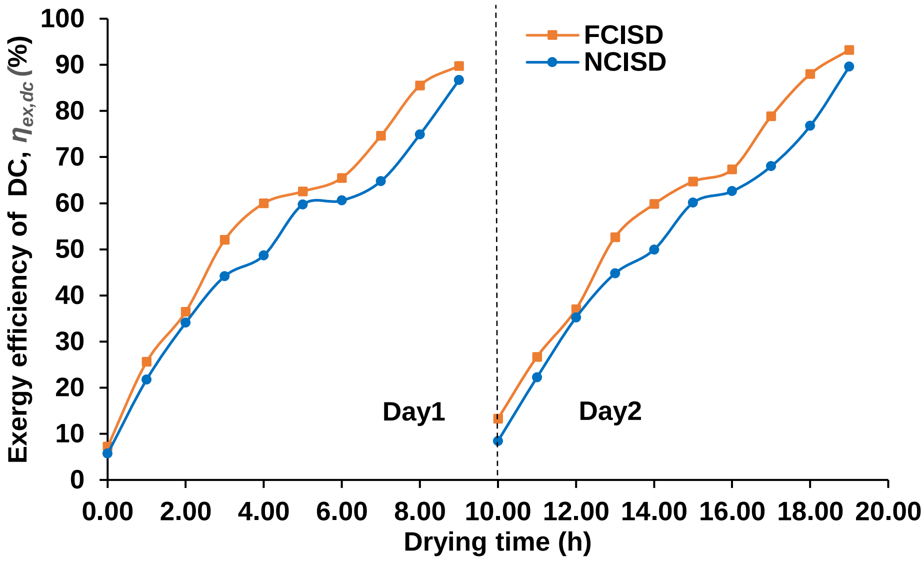


Fig. 4.21. Change in $\eta_{ex,dc}$ with drying time in ISD during drying guava slices

Exergy sustainability indicators

The indicators including improvement potential (IP), environmental impact factor (EIF), sustainability index (SI) and waste exergy ratio (WER) are evaluated for drying chamber in NCISD and FCISD during drying guava, muskmelon and beetroot slices. The variation of IP and EIF with drying time in NCISD and FCISD during drying guava slices is shown in **Fig. 4.22**. The higher EIF results in higher damage to the environment [13]. EIF is inversely proportional to $\eta_{ex,dc}$, so it is decreased with drying time (**Fig. 4.22**). The higher values of EIF are observed in NCISD compared to FCISD since higher temperature drop (i.e., higher exergy losses) in the drying chamber occurred due to the lower velocity of air in NCISD. The higher exergy losses indicate a higher potential for improvement of the drying process. The IP values are higher in NCISD in contrast to FCISD because greater exergy losses occurred in NCISD.

The SI indicates the amount of exergy supplied per unit loss of exergy. The WER is a reciprocal of SI and gives the amount of exergy lost per unit of exergy supplied. The change in SI and WER with time in NCISD and FCISD during drying guava slices was shown in **Fig. 4.23**. As time progresses, the WER decreases and SI increases in both setups (**Fig. 4.23**). In FCISD, the values of SI are higher and whereas in NCISD, the values of WER are higher.

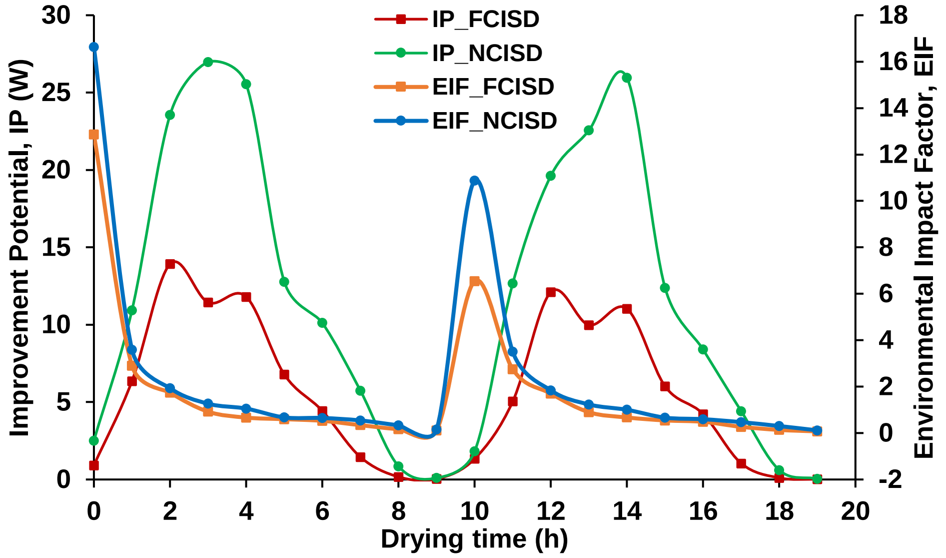


Fig. 4.22. Change in IP and EIF with time in NCISD and FCISD during drying guava slices

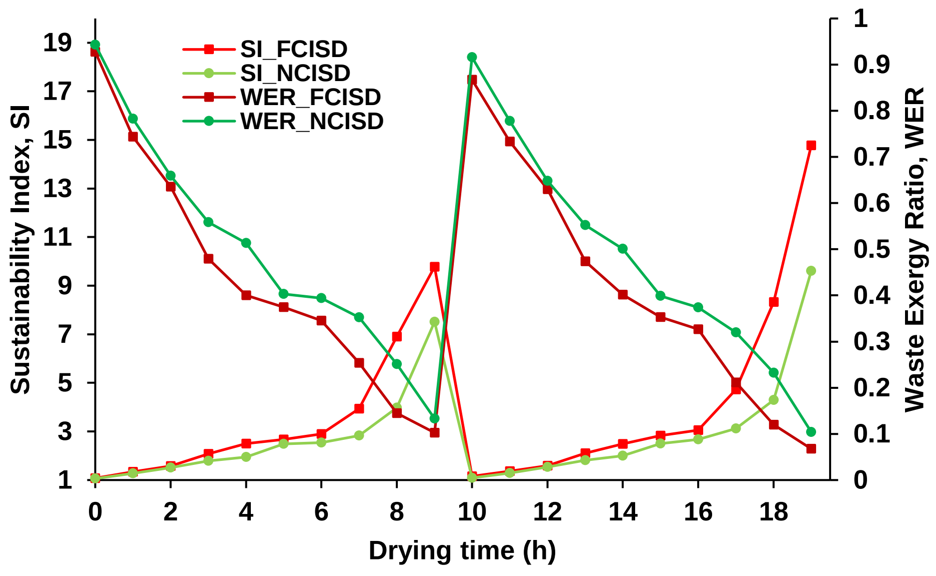


Fig. 4.23. Change in SI and WER with time in NCISD and FCISD during drying guava slices

The ranges and averages of IP, EIF, WER and SI in NCISD and FCISD during drying guava, muskmelon and beetroot were mentioned in **Table 4.5.** It is observed that values of IP, EIF, SI and WER were in a similar range reported in the literature (**Table 4.5**). The average decrement of 52.46% on IP, 26.16% on EIF and 12.24% on WER, and average increment of 35.92% on SI were noticed in FCISD compared to NCISD during drying guava slices. Similar observations were noticed during drying muskmelon and beetroot slices. The higher value of SI and lower values of WER, EIF and IP indicate that the exergetic performance of ISD is enhanced by forced mode compared to natural mode setup.

Table 4.5. Values of exergy sustainability indicators in NCISD and FCISD without TES device

Indicator	Sample	NCISD		FCISD		Literature
		Range	Avg.	Range	Avg.	
IP (W)	Guava	0.04−26.98	11.38	0.01−11.8	5.41	0.24−7.92 W [111], 0.5 to 41 W [123]
	Muskmelon	0.11−29.10	11.56	0.01−11.35	5.37	
	Beetroot	0.21−29.60	12.06	0.06−14.88	6.17	
EIF	Guava	0.11−16.63	2.37	0.07−12.87	1.75	11.28−40.35 [13], 0.16−2.4 [84]
	Muskmelon	0.20−15.51	2.93	0.07−7.90	1.79	
	Beetroot	0.20−20.38	2.74	0.14−14.20	2.07	
WER	Guava	0.1−0.94	0.49	0.07−0.93	0.43	0.10−0.30 [13], 0.38−0.55 [122]
	Muskmelon	0.17−0.94	0.54	0.06−0.88	0.44	
	Beetroot	0.17−0.95	0.51	0.12−0.93	0.45	
SI	Guava	1.06−9.61	2.84	1.08−14.78	3.86	1.09−4.77 [111], 3.93−4.97 [124]
	Muskmelon	1.06−5.81	2.29	1.12−14.78	3.68	
	Beetroot	1.05−5.90	2.56	1.07−8.06	3.06	

4.2.5. Summary of results in NCISD and FCISD without TES

The drying kinetics and energy and exergy analysis of NCISD and FCISD without TES are compared and assessed. The values of different parameters found in NCISD and FCISD without TES and their increment/decrement with respect to NCISD during drying guava, muskmelon and beetroot slices are summarised in **Table 4.6.** The average values of T_{co} and T_{dc}, initial and final MC of samples and drying duration during drying guava, muskmelon and beetroot were found in NCISD and FCISD. Also, the drying kinetics such as DR, D_{ef}, h_{mt}. h_{ht} and E_{ac} were found in both setups. In the energy and exergy analysis, parameters such as $\eta_{en,SAC}$, $\eta_{en,dry}$, SEC, SMER, $\eta_{ex,SAC}$, $\eta_{ex,dc}$, IP, EIF, WER and SI were found in both setups.

The average DR, D_{ef}, h_{mt}, h_{ht}, $\eta_{en,SAC}$, $\eta_{en,dry}$, $\eta_{ex,dc}$ and SI are higher in FCISD compared to NCISD because of higher velocity of air which was produced by direct current fans at the entrance of the SAC. The other parameters such as average T_{co}, T_{dc}, E_{ac}, SEC, $\eta_{ex,SAC}$, IP, EIF and WER are lower in FCISD compared to NCISD. Drying duration was reduced in FCISD (4 h for guava, and 3 h for muskmelon and beetroot) compared to NCISD. From **Table 4.6**, the drying kinetics of food products and parameters found in energy and exergy analysis were improved in FCISD compared to NCISD.

Table 4.6. Results comparison of NCISD and FCISD without TES device

Parameter (average)	**Sample**	**NCISD**	**FCISD**	**% increase/decrease**
T_{co} (°C)	Guava	57.45	52.55	8.53 (decrease)
	Muskmelon	54.58	51.20	6.19 (decrease)
	Beetroot	56.97	53.22	6.58 (decrease)
T_{dc} (°C)	Guava	49.93	45.14	9.59 (decrease)
	Muskmelon	46.7	42.94	8.05 (decrease)
	Beetroot	47.60	45.55	4.31 (decrease)
MC (db)		Initial	Final	
	Guava	5.5355	0.0244	-
	Muskmelon	12.4156	0.1605	-
	Beetroot	7.7535	0.0569	-
Drying duration (h)	Guava	18	14	22.22 (decrease)
	Muskmelon	18	15	16.67 (decrease)
	Beetroot	18	15	16.67 (decrease)
DR (kg/h)	Guava	0.3062	0.3936	28.54 (increase)
	Muskmelon	0.6808	0.8170	20.01 (increase)
	Beetroot	0.4276	0.5131	19.99 (increase)
D_{ef} (m^2/s)	Guava	5.95×10^{-9}	7.98×10^{-9}	34.12 (increase)
	Muskmelon	2.45×10^{-8}	3.04×10^{-8}	24.08 (increase)
	Beetroot	5.90×10^{-9}	7.11×10^{-9}	20.30 (increase)
h_{mt} (m/s)	Guava	2.70×10^{-3}	4.20×10^{-3}	55.55 (increase)
	Muskmelon	2.81×10^{-3}	4.36×10^{-3}	55.16 (increase)

	Beetroot	2.67×10^{-3}	3.56×10^{-3}	33.33 (increase)
h_{ht} (W/m^{2}K)	Guava	3.112	4.842	55.59 (increase)
	Muskmelon	3.235	5.026	55.36 (increase)
	Beetroot	3.081	4.103	33.17 (increase)
E_{ac} (kJ/mol)	Guava	136.98	116.49	14.96 (decrease)
	Muskmelon	38.06	28.61	24.83 (decrease)
	Beetroot	27.57	23.22	15.78 (decrease)
$\eta_{en,SAC}$ (%)	Guava	56.05	65.37	16.63 (increase)
	Muskmelon	58.50	66.37	13.45 (increase)
	Beetroot	65.62	71.09	8.34 (increase)
$\eta_{en,dry}$ (%)	Guava	7.71	10.26	33.07 (increase)
	Muskmelon	9.39	11.37	21.09 (increase)
	Beetroot	9.49	11.31	19.18(increase)
SEC (kWh/kg)	Guava	2.108	1.675	20.54 (decrease)
	Muskmelon	1.838	1.612	12.30 (decrease)
	Beetroot	1.947	1.706	12.38 (decrease)
SMER (kg/kWh)	Guava	0.474	0.597	25.95 (increase)
	Muskmelon	0.544	0.620	13.97 (increase)
	Beetroot	0.514	0.586	14.23 (increase)
$\eta_{ex,SAC}$ (%)	Guava	3.73	2.39	35.92 (decrease)
	Muskmelon	3.46	2.43	29.77 (decrease)
	Beetroot	4.21	2.80	33.49 (decrease)
$\eta_{ex,dc}$ (%)	Guava	50.92	57.03	11.99 (increase)
	Muskmelon	45.87	55.73	21.50 (increase)
	Beetroot	49.43	54.92	11.11 (increase)
IP (W)	Guava	11.38	5.41	52.46 (decrease)
	Muskmelon	11.56	5.37	53.55 (decrease)
	Beetroot	12.06	6.17	48.84 (decrease)
EIF	Guava	2.37	1.75	26.16 (decrease)
	Muskmelon	2.93	1.79	38.90 (decrease)
	Beetroot	2.74	2.07	24.45 (decrease)
	Guava	0.49	0.43	12.24 (decrease)

WER	Muskmelon	0.54	0.44	18.52 (decrease)
	Beetroot	0.51	0.45	11.76 (decrease)
SI	Guava	2.84	3.86	35.92 (increase)
	Muskmelon	2.29	3.68	60.69 (increase)
	Beetroot	2.56	3.06	19.53 (increase)

4.3. FCISD without and with TES

4.3.1. Solar radiation data

Initially guava, muskmelon, beetroot and green chilli were dried in FCISD without TES device (model-1). Next, the samples were dried in FCISD with TES device (model-2). For model-1, experiments were conducted for two days from 8.00 am to 5.00 pm with a duration of 9 h in a day. In model-1, 0.00 and 9.00 h in the X-axis of **Fig. 4.24** denote 8.00 am and 5.00 pm for Day-1, and 10.00 and 19.00 h denote the same for Day-2, respectively. For model-2, the experiments were started at morning 8.00 am and ended at midnight and these are denoted by 0.00 and 16.00 h in the X-axis of **Fig. 4.24**, respectively. The measured I_s during drying guava in model-1 and model-2 is shown in **Fig. 4.24**. During drying guava, the average I_s was 682.1 and 693.1 W/m^2 in model-1 and model-2, respectively. Similarly, during drying muskmelon, beetroot and chilli, the average I_s was 666.05 and 673.8 W/m^2, 681.45 and 685.3 W/m^2, 658.15 and 670.3 W/m^2, in model-1 and model-2, respectively. Since the experiments were performed on consecutive days, the average I_s was found to be almost the same in both models.

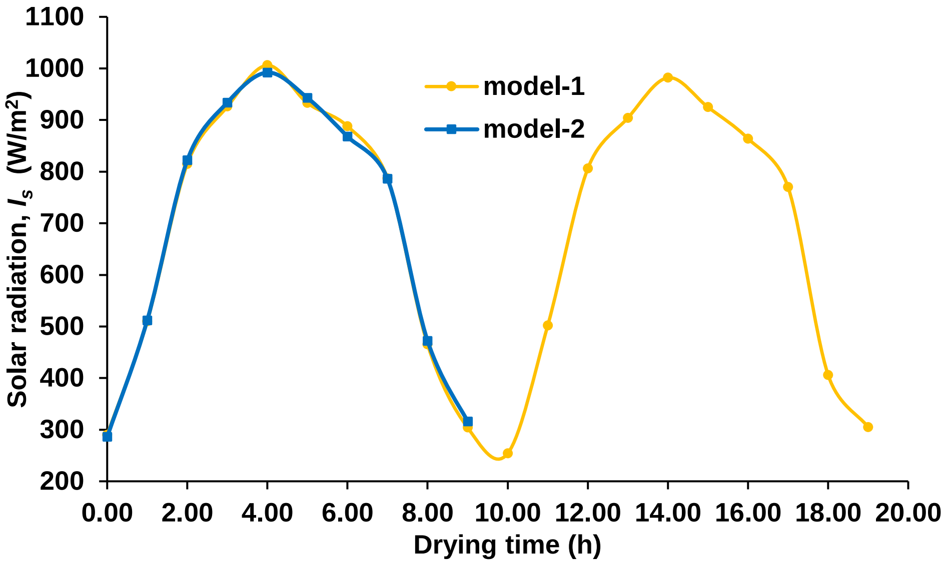


Fig. 4.24. Variation of solar radiation data in both models during drying guava

4.3.2. Temperature distribution

The temperatures were measured at various locations in model-1 and model-2 are measured during drying guava, muskmelon, beetroot and green chilli. During drying guava in model-1, the temperatures T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were measured and reported in **Fig. 4.3.** During drying guava in model-1, the average values of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were 38.24, 38.85, 52.55, 47.50, 45.95, 44.25 and 42.85 °C, respectively. In model-2, the average values of T_{amp}, T_{ci}, T_{co}, T_{tr1}, T_{tr2}, T_{tr3} and T_{tr4} were 37.13, 37.38, 45.55, 43.59, 42, 40.65 and 39.82°C, respectively (**Fig. 4.25**). The higher temperatures of the same were 44.5, 44.6, 69.9, 56, 54, 52 and 50 °C, respectively. Similarly, during drying muskmelon in model-2, the average values of the same were 37.07, 37.24, 45.75, 44.35, 42.76, 41.41 and 40.12 °C, respectively. While drying beetroot in model-2, the average values of the same were 34.62, 34.86, 43.65, 42.71, 41, 39.71 and 38.47 °C, respectively. During drying chilli in model-2, the average values of the same were 32.35, 32.78, 41.56, 40.71, 39, 37.47, 36.12 °C, respectively. The paraffin wax as a phase change material (PCM) in TES absorbs the heat energy from the air inside the dryer and hence temperatures are lower in model-2 compared to model-1. From 01.00 pm to 5.00 pm, the T_{r1} value was ranged from 38 to 57 °C and 41 to 56 °C, in model-1 and model-2, respectively during drying guava slices. A similar variation was noticed for T_{r2}, T_{r3} and T_{r4}. It shows that TES maintains almost constant temperature in model-2 due to absorption and release of heat by PCM.

From **Fig. 4.25**, it is observed that heat is discharged from TES after 5.00 pm (9 h in X-axis) of the day and increased the T_{co} by 1.2 to 7.7 °C till midnight. The temperature of paraffin wax (T_{pw}) was observed from 33 to 47 °C during drying guava slices from morning 8.00 am to midnight. The average T_{pw} decreased by 4.2 °C from 5.00 pm to midnight. The temperature difference between atmosphere and average T_{pw} was ranged from 7.2 to 11.1 °C from 6.00 pm to midnight. The T_{dc} was 2.5 to 6.8 °C higher than T_{amp} from 6.00 pm to midnight during drying guava slices. Similarly, during drying muskmelon, beetroot and chilli in model-2, T_{dc} was maintained to be 3−7.9 °C, 5.8−8.5 °C and 5.4−7.7 °C higher than T_{amp}, respectively. The results were found to be better compared to the studies in literature, where the T_{dc} was maintained to be 6 °C [58] and 2.5−7.5 °C [62] higher than T_{amp} after the sunset due to TES.

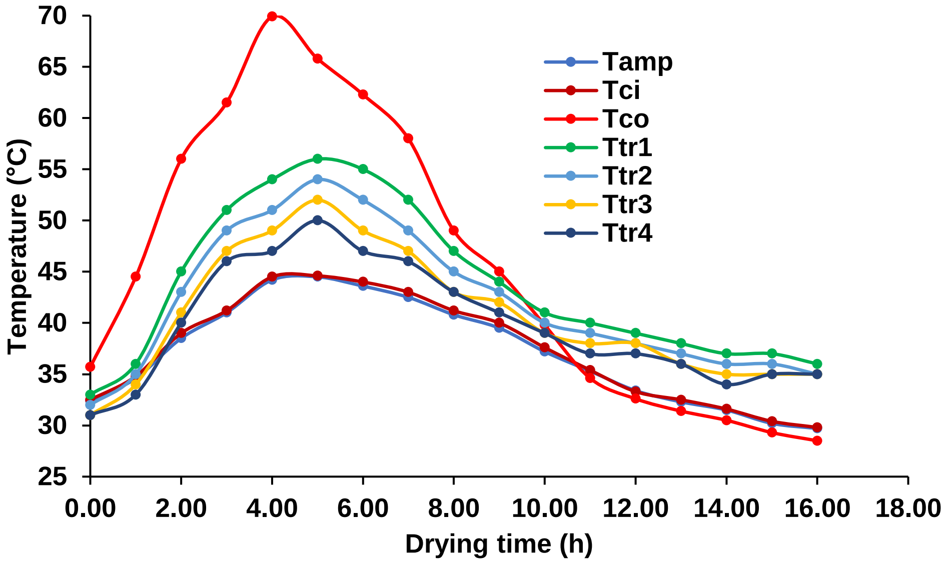


Fig. 4.25. Temperature distribution in model-2 during drying guava

4.3.3. Drying kinetics

4.3.3.1. Moisture content (MC)

The final MCs achieved in model-1 and model-2 were determined and compared during drying guava, muskmelon, beetroot and chilli. During drying guava, the final MCs reached in model-1 and model-2 were 0.0244 and 0.0342 db, respectively, and it is achieved by using 14 and 9 sunshine hours respectively. Similarly, during drying muskmelon, beetroot and chilli, the final MCs were 0.1604 and 0.2108 db, 0.0569 and 0.0767 db, 0.1137 and 0.1513 db, in model-1 and model-2, respectively. During drying muskmelon, beetroot and chilli, the final MC achieved by using 15 and 9 sunshine hours in model-1 and model-2, respectively. In model-2, all samples were dried for another 7 non-sunshine hours.

4.3.3.2. Samples dried in ISD and OSD

It is noticed that quality of samples dried in ISD without and with TES were found to be same. The snapshots of guava, beetroot and muskmelon dried in ISD without TES and OSD are already discussed in the previous section (4.2.3.2. samples dried in ISD and OSD). The snapshot of green chilli dried in ISD and OSD is shown in **Fig. 4.26.** The final MC of chilli was achieved in 27 h in OSD method. It is noticed that the natural colour of the product was lost in OSD method compared to ISD method. It is also noticed that more dust on the products which was dried in OSD method as the products were exposed in direct sun and open environment.

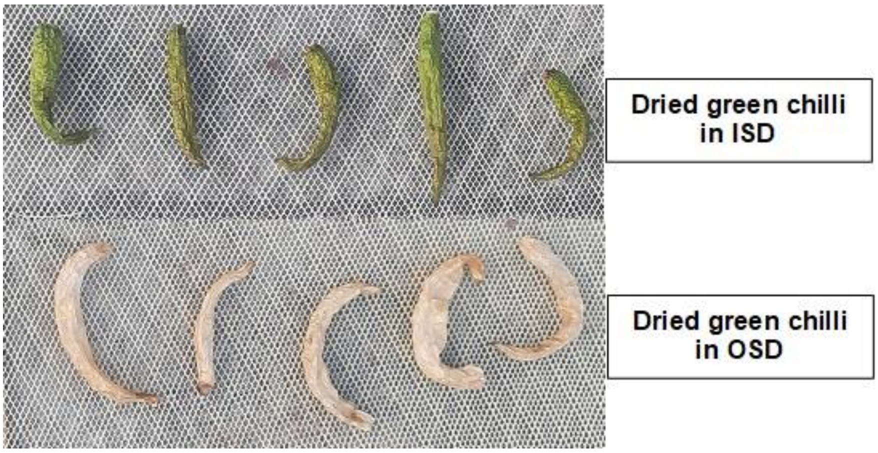


Fig. 4.26. Snapshot of green chilli samples dried in ISD and OSD

4.3.3.3. Drying rate (DR)

The DR is evaluated in model-1 and 2 during drying guava, muskmelon, beetroot and chilli. The variation of DR with drying time during drying guava in model-1 and model-2 is shown in **Fig. 4.27**. In the afternoon session, the D_R values were higher in model-2 comparatively model-1 due to constant drying air temperature was maintained as the heat released from the PCM in model-2. During drying guava, the average and maximum DR were noticed to be 0.3936 & 1.0702 kg/h and 0.5728 & 1.0146 kg/h, in model-1 and model-2, respectively. In model-2 the average D_R was increased by 45.53% in day time by comparing with model-1 due to higher moisture lost from 2.00 pm to 5.00 pm (6.00 to 9.00 h in X-axis) in model-2. Similarly, during drying muskmelon, the average and maximum DR were 0.8170 & 2.119 kg/h and 1.2585 & 1.898 kg/h, in model-1 and model-2, respectively. During drying beetroot, the same were 0.5131 & 1.0964 kg/h and 0.7268 & 1.004 kg/h, respectively. During drying chilli, the same were 0.5523 & 1.2042 kg/h and 0.7661 & 1.069 kg/h, respectively. In model-2, the DR is improved by 54.04%, 41.65% and 38.71% compared to model-1 during drying muskmelon, beetroot and chilli, respectively.

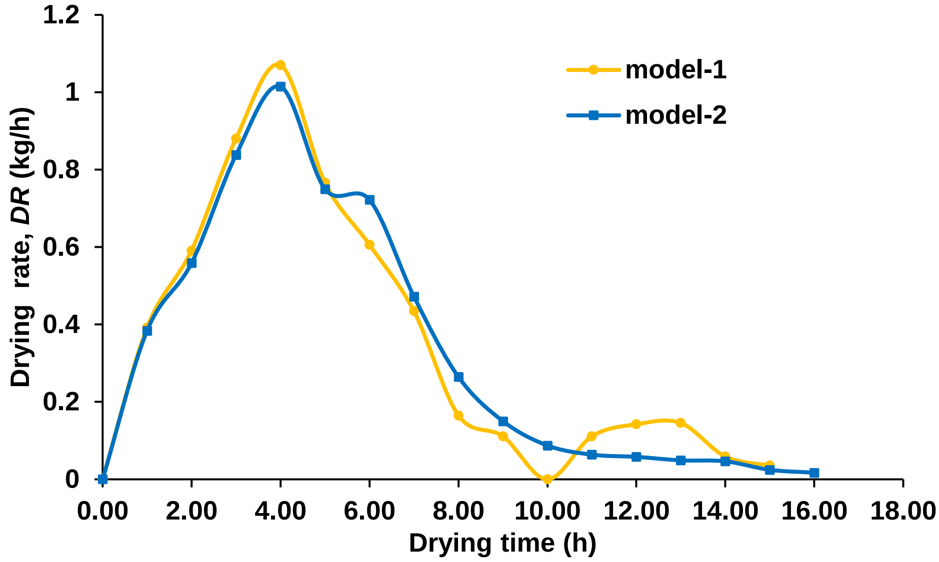


Fig. 4.27. Change of DR with time in model-1 and 2 during drying guava

4.3.3.4. Moisture ratio (MR)

The MR of guava, muskmelon, beetroot and chilli for each tray in the drying chamber and OSD was evaluated using 12 models in model-1 and model-2. The best accurate model was decided by finding the model with higher R^2 and lower χ^2. The perfect drying model to describe the drying kinetics of guava, muskmelon, beetroot and chilli in model-1 was Page, Two-term exponential, Two-term exponential and Two-term exponential, respectively. The regression results of best six models to describe the drying kinetics of guava, muskmelon and beetroot in model-1 are discussed in the previous section (4.2.3.3, moisture ratio). The best model to describe the drying kinetics of guava, muskmelon, beetroot and chilli in model-2 was Page, Page, Page and modified Page model, respectively. For the best model in model-2, the values of R^2 = 0.99922, 0.99809, 0.99919 and 0.99850, and χ^2 = 0.00010, 00023, 0.00011 and 0.00021 were found for guava, muskmelon, beetroot and chilli, respectively. The next best two models to describe drying kinetics of guava, muskmelon, beetroot and chilli in model-2 were Verma and Two-term exponential models. The regression results of best six models to describe the drying kinetics of guava, muskmelon, beetroot and chilli in model-2 are described in **Tables**

4.7, 4.8, 4.9 and 4.10, respectively. The fitting of the best model with experimental data of guava, muskmelon, beetroot and chilli in model-2 is shown in **Fig. 4.28.**

Table 4.7. Regression results of best six models for guava in model-2

Model name	Tray no	constants	R^2	χ^2
Page model	Tray 1	k = 0.0696; n =1.80672	**0.99922**	**0.00010**
	Tray 2	k = 0.05899; n = 1.80623	**0.99766**	**0.00029**
	Tray 3	k = 0.05439; n = 1.77648	0.99776	0.00028
	Tray 4	k = 0.05268; n = 1.71741	0.99705	0.00037
	OSD	k = 0.09279; n = 1.09177	0.97548	0.00192
Modified Page	Tray 1	k = 0.22876; n = 1.80684	**0.99922**	**0.00010**
	Tray 2	k = 0.20867; n = 1.80519	**0.99766**	**0.00029**
	Tray 3	k = 0.19420; n = 1.77464	0.99776	0.00028
	Tray 4	k = 0.18016; n = 1.71503	0.99705	0.00037
	OSD	k = 0.11331; n = 1.090958	0.97548	0.00192
Verma model	Tray 1	k = 0.54445; g = 0.55293; a = 78.2176	0.99553	0.00055
	Tray 2	k = 0.49528; g = 0.50479; a = 63.86687	0.99495	0.00064
	Tray 3	k=0.46256; g = 0.47411; a = 50.04477	0.99721	0.00035
	Tray 4	k = 0.42334; g = 0.43687; a = 38.53753	0.99759	0.00030
	OSD	k = 0.12578; g = 2.88341; a = 1.09599	0.98101	0.00149
Two-term exponential	Tray 1	k = 0.40202; a = 2.17076	0.99378	0.00077
	Tray 2	k = 0.36574; a = 2.17363	0.99345	0.00082
	Tray 3	k = 0.34224; a = 2.18782	0.99606	0.00050
	Tray 4	k = 0.31551; a = 2.17202	0.99677	0.00041
	OSD	k = 0.14003; a = 1.54902	0.97375	0.00205
Wang and Singh	Tray 1	a =-0.16917; b = 0.0069	0.97790	0.00273
	Tray 2	a = -0.15766; b = 0.00611	0.97589	0.00303
	Tray 3	a = -0.14842; b = 0.00548	0.97555	0.00311
	Tray 4	a = -0.13873; b = 0.00484	0.97610	0.00302
	OSD	a = -0.09965; b = 0.00306	0.97495	0.00196
Logarithmic	Tray 1	k = 0.22508; a = 1.18324; c = -0.07822	0.96633	0.00416
	Tray 2	k = 0.19895; a = 1.19885; c = -0.09267	0.96527	0.00436
	Tray 3	k = 0.18077; a = 1.21898; c = -0.10754	0.96781	0.00410
	Tray 4	k = 0.16169; a = 1.23562; c = -0.12803	0.97080	0.00370
	OSD	k = 0.1353; a = 1.01058; c = 0.05521	0.97775	0.00174

Table 4.8. Regression results of best six models for muskmelon in model-2

Model name	Tray no	constants	R^2	χ^2
Page model	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.07493; n =1.62959 k = 0.05053; n = 1.77551 k = 0.04902; n = 1.75783 k = 0.05015; n = 1.70534 k = 0.06403; n = 1.27598	**0.99809** 0.99823 0.99758 0.99674 0.98093	**0.00023** 0.00022 0.00031 0.00041 0.00174
Modified Page	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.20391; n = 1.62939 k = 0.18614; n = 1.77484 k = 0.17988; n = 1.75702 k = 0.17293; n = 1.70351 k = 0.11602; n = 1.2746	0.99809 0.99823 0.99758 0.99674 0.98093	0.00023 0.00022 0.00031 0.00041 0.00174
Verma model	Tray 1	k = 0.46256; g = 0.47231; a = 53.20452	0.99660	0.00041
	Tray 2	k = 0.43817; g = 0.44668; a= 62.12541	0.99546	0.00057
	Tray 3	k = 0.42285; g = 0.43209; a = 55.41056	0.99586	0.00052
	Tray 4	k = 0.40313; g = 0.41521; a = 40.35586	0.99688	0.00039
	OSD	k = 0.14292; g = 1.18927; a = 1.22142	0.98752	0.00114
Two-term exponential	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.34794; a = 2.10387 k= 0.32436; a = 2.15909 k= 0.31339; a = 2.16116 k = 0.30065; a = 2.15689 k= 0.17662; a = 1.89086	0.99557 0.99386 0.99448 0.99601 0.98215	0.00054 0.00078 0.00070 0.00050 0.00163
Wang and Singh	Tray 1 Tray 2 Tray 3 Tray 4 OSD	a =-0.15496; b = 0.00593 a = -0.14424; b = 0.00521 a = -0.13955; b = 0.0049 a = -0.13408; b = 0.00455 a = -0.09234; b = 0.00233	0.98649 0.97786 0.97641 0.9760 0.97293	0.00164 0.0028 0.00298 0.00301 0.00248
Logarithmic	Tray 1	k = 0.19165; a = 1.1860; c = -0.09505	0.97512	0.00301
	Tray 2	k = 0.16853; a = 1.22641; c = -0.1232	0.96753	0.00411
	Tray 3	k = 0.16046; a = 1.23501; c = -0.13145	0.96797	0.00405
	Tray 4	k = 0.15211; a = 1.24187; c = -0.13862	0.9703	0.00372
	OSD	k = 0.10282; a = 1.18874; c = 0.11713	0.97658	0.00214

Table 4.9. Regression results of best six models for beetroot in model-2

Model name	Tray no	constants	R^2	χ^2
Page model	Tray 1 Tray 2 Tray 3	k = 0.03665; n =1.85158 k = 0.2870; n = 1.90507 k = 0.02772; n = 1.89292	**0.99919** 0.99925 0.99901	**0.00011** 0.00010 0.00013

	Tray 4 OSD	k = 0.02366; n = 1.91369 k = 0.0516; n = 1.20544	0.99829 0.98455	0.00023 0.00101
Modified Page model	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.16768; n =1.85017 k = 0.15506; n = 1.9022 k = 0.15045; n = 1.88948 k = 0.14137; n = 1.90962 k = 0.08552; n = 1.20574	0.99919 0.99925 0.99901 0.99829 0.98455	0.00011 0.00010 0.00013 0.00023 0.00101
Verma model	Tray 1	k = 0.40801; a = 70.81027; g = 0.41538	0.99580	0.00057
	Tray 2	k = 0.38018; a = 71.86461; g = 0.38708	0.99528	0.00064
	Tray 3	k = 0.36856; a = 68.48571; g = 0.37558	0.99572	0.00058
	Tray 4	k = 0.34669; a = 69.50211; g = 0.35323	0.99436	0.00076
	OSD	k = 0.14656; a = 17.12116; g = 0.15229	0.98274	0.00113
Two-term exponential	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 2.1132; a = 2.20963 k = 2.1247; a = 2.22413 k = 2.1173; a = 2.22439 k = 2.0948; a = 2.22656 k = 0.11933; a = 1.74815	0.99352 0.99271 0.99327 0.99171 0.98382	0.00087 0.00099 0.00091 0.00111 0.00106
Wang and Singh	Tray 1 Tray 2 Tray 3 Tray 4 OSD	a = -0.1286; b = 0.00406 a = -0.11718; b = 0.00331 a = -0.11276; b = 0.00303 a = -0.10334; b = 0.00242 a =-0.06488; b = 0.00097	0.97347 0.96798 0.96740 0.96470 0.98525	0.00358 0.00434 0.00440 0.00473 0.00097
Logarithmic	Tray 1	k = 0.13485; a = 1.32328 c = -0.21208	0.97069	0.00395
	Tray 2	k = 0.11525; a = 1.38713 c = -0.27488	0.96916	0.00418
	Tray 3	k = 0.10837; a = 1.41230 c = -0.30089	0.97006	0.00404
	Tray 4	k = 0.09241; a = 1.49578 c = -0.38793	0.96959	0.00407
	OSD	k = 0.04983; a = 1.47081 c = -0.44856	0.98573	0.00093

Table 4.10. Regression results of best six models for green chilli in model-2

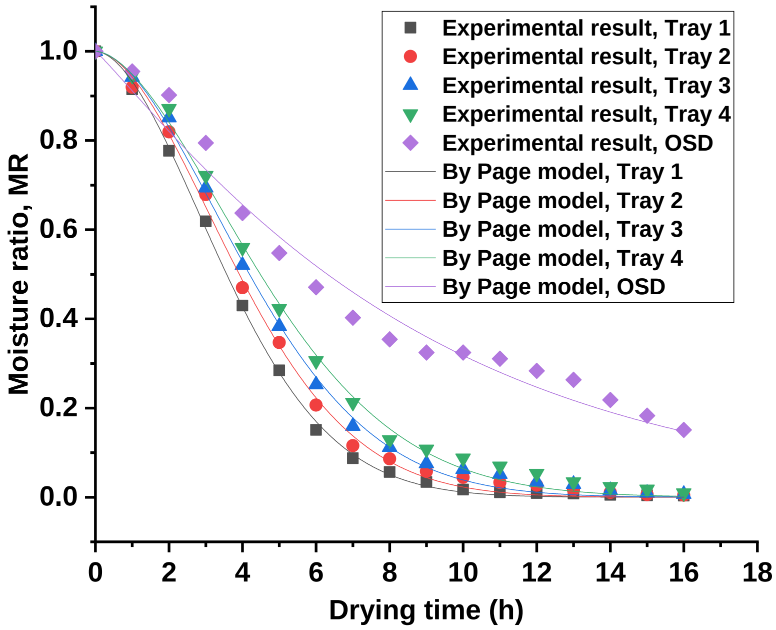
Model name	**Tray no**	**constants**	R^2	χ^2
Modified Page model	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.17087; n = 2.08171 k = 0.15299; n = 2.02118 k = 0.13733; n = 1.84209 k = 0.12946; n = 1.80335 k = 0.07357; n = 1.44315	**0.99850** 0.99929 0.99897 0.99869 0.98481	**0.00021** 0.00010 0.00014 0.00017 0.00092
Page model	Tray 1 Tray 2 Tray 3	k = 0.02529; n = 2.08132 k = 0.02242; n = 2.02284 k = 0.02579; n = 1.84501	0.99850 0.99929 0.99897	0.00021 0.00010 0.00014

	Tray 4 OSD	k = 0.02496; n = 1.80515 k = 0.01409; n = -121886.8	0.99869 -3.60636	0.00017 0.27884

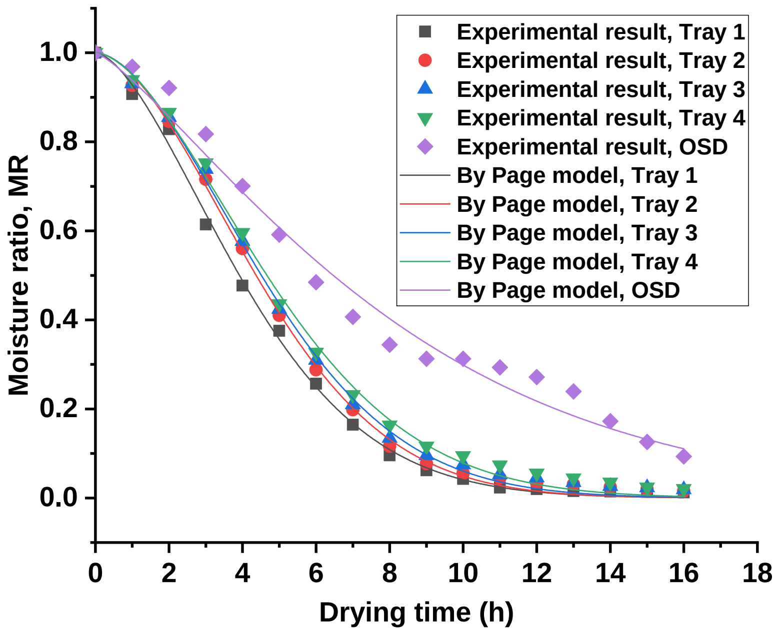
Verma model	Tray 1
	
	Tray 2
	
	Tray 3
	
	Tray 4
	
	OSD
		k = 0.42647; a = 104.9534;
		g = 0.4319
		k = 0.38093; a = 87.91828;
		g = 0.38673
		k = 0.33595; a = 59.43609;
		g = 0.34329
		k = 0.31294; a = 52.69306;
		g = 0.32055
		k = 0.10393; a = 1.5718;
		g = 0.27725
			0.98845
			
			0.9917
			
			0.99737
			
			0.99782
			
			0.98359
				0.00162
				
				0.00116
				
				0.00034
				
				0.00027
				
				0.00099

Two-term exponential	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.30852; a = 2.24518 k = 0.27592; a = 2.24637 k = 0.24605; a = 2.22035 k = 0.2301; a = 2.2082 k = 0.11417; a = 1.95584	0.9851 0.98841 0.99522 0.99598 0.98466	0.0021 0.00162 0.00063 0.00051 0.00092
Wang and Singh	Tray 1 Tray 2 Tray 3 Tray 4 OSD	a = -0.1324; b = 0.0043 a = -0.11542; b = 0.00317 a = -0.09957; b = 0.00219 a = -0.09044; b = 0.00163 a =-0.043431; b = -0.00021	0.96214 0.96159 0.96928 0.97257 0.9816	0.00533 0.00536 0.00405 0.00351 0.00111
Logarithmic	Tray 1 Tray 2 Tray 3 Tray 4 OSD	k = 0.13928; a = 1.33307 c = -0.21142 k = 0.11054; a = 1.42212 c = -0.30485 k = 0.08769; a = 1.52208 c = -0.41497 k = 0.07329; a = 1.63747 c = -0.53688 k = 0.00879; a = 5.90030 c = -4.86570	0.95685 0.96321 0.97578 0.98050 0.98361	0.00607 0.00513 0.00319 0.00250 0.00099

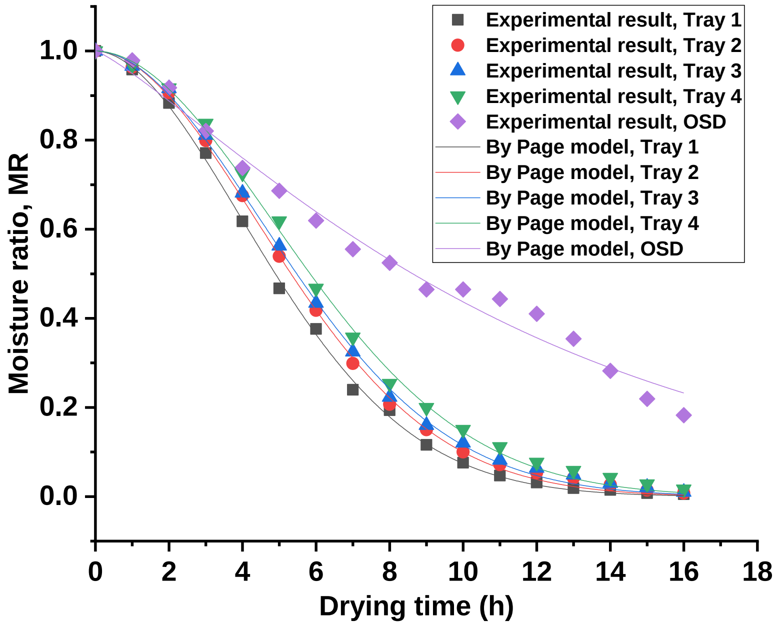
(a)


Experimental result, Tray 1
Experimental result, Tray 2
Experimental result, Tray 3
Experimental result, Tray 4
Experimental result, OSD
By Page model, Tray 1
By Page model, Tray 2
By Page model, Tray 3
By Page model, Tray 4
By Page model, OSD
Moisture ratio, MR
Drying time (h)

(b)


Experimental result, Tray 1
Experimental result, Tray 2
Experimental result, Tray 3
Experimental result, Tray 4
Experimental result, OSD
By Page model, Tray 1
By Page model, Tray 2
By Page model, Tray 3
By Page model, Tray 4
By Page model, OSD
Moisture ratio, MR
Drying time (h)

(c)



(d)

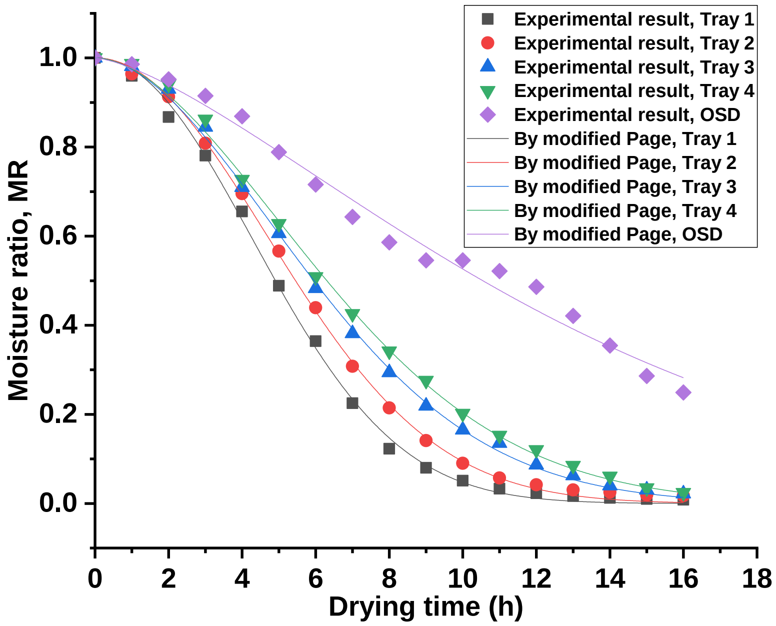


Fig. 4.28. Drying curves fitted with best model while drying (a) guava (b) muskmelon (c) beetroot and (d) chilli in model-2

4.3.3.5. Effective diffusion coefficient (D_{ef})

The D_{ef} was determined for guava, muskmelon, beetroot and chilli in model-1 and model-2. During drying guava, the D_{ef} varied $2.29 \times 10^{-9} - 1.76 \times 10^{-8}$ m^2/s and $2.29 \times 10^{-9} - 1.66 \times 10^{-8}$ m^2/s in model-1 and model-2, respectively as shown in **Fig. 4.29**. Higher D_{ef} values were observed in model-2 in comparison with model-2 after 4.00 pm (8.00 h in X-axis), since a greater amount of MC is eliminated after the sunset due to heated air from the TES device. The average D_{ef} of guava was 7.98 × 10^{-9} m^2/s in model-1 and in model-2, it was 8.63 × 10^{-9} m^2/s with an increment of 8.15%. The average value of D_{ef} was found to be higher in model-2, because the drying duration is higher in model-2 and D_{ef} value increases with time. Similarly, during drying muskmelon, the range of D_{ef} was ranged from 9.14 × 10^{-9} to 5.82 × 10^{-8} m^2/s and 5.51 × 10^{-8} m^2/s, in model-1 and model-2, respectively. The average D_{ef} of muskmelon was 3.04 × 10^{-8} and 3.13 × 10^{-8} m^2/s in model-1 and 2, respectively. During drying beetroot, the D_{ef} ranged from 2.29 × 10^{-9} to 1.62 × 10^{-8} m^2/s and 1.53 × 10^{-8} m^2/s in model-1 and model-2, respectively. The average D_e was noted to be 7.11 × 10^{-9} m^2/s in model-1 and 7.22 × 10^{-9} m^2/s in model-2 with an increment of 1.55%. During drying chilli, the range of D_{ef} was from 5.72 × 10^{-10} to 3.60 × 10^{-9} m^2/s and 3.40 × 10^{-9} m^2/s, in model-1 and model-2, respectively. The average D_e was noted to be 1.68 × 10^{-9} m^2/s in mode-I and 1.71 × 10^{-9} m^2/s in mode-II with an increment of 1.55%. The D_e values observed in the current study are similar to the findings reported by Hadibi et al. [13] for garlic cloves (0.264 to 2.063 ×10^{-9} m^2/s) and Mathew and Thangavel [125] for tomato slices (2.3 to 3.8 × 10^{-9} m^2/s).

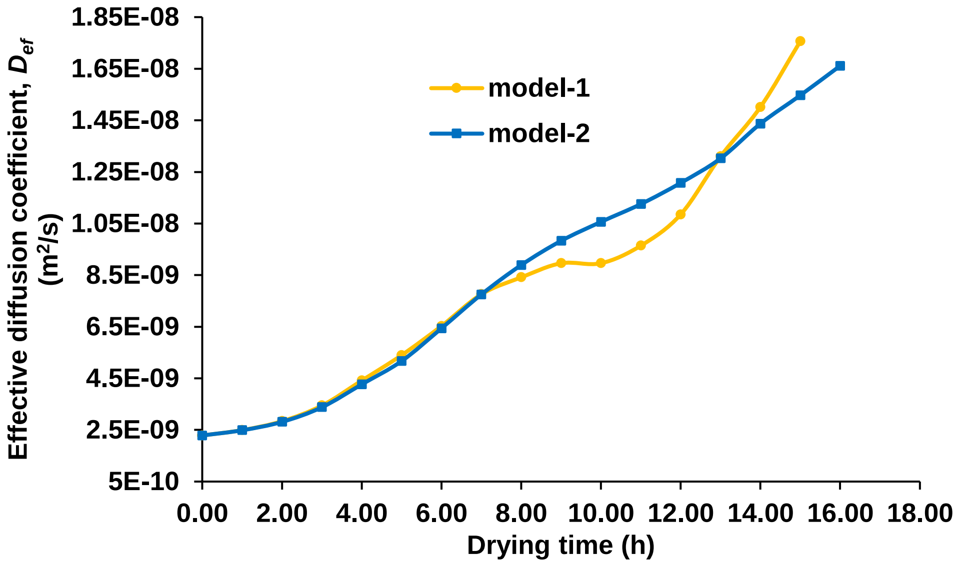


Fig. 4.29. Change of D_{ef} with drying time during guava in model-1 and 2

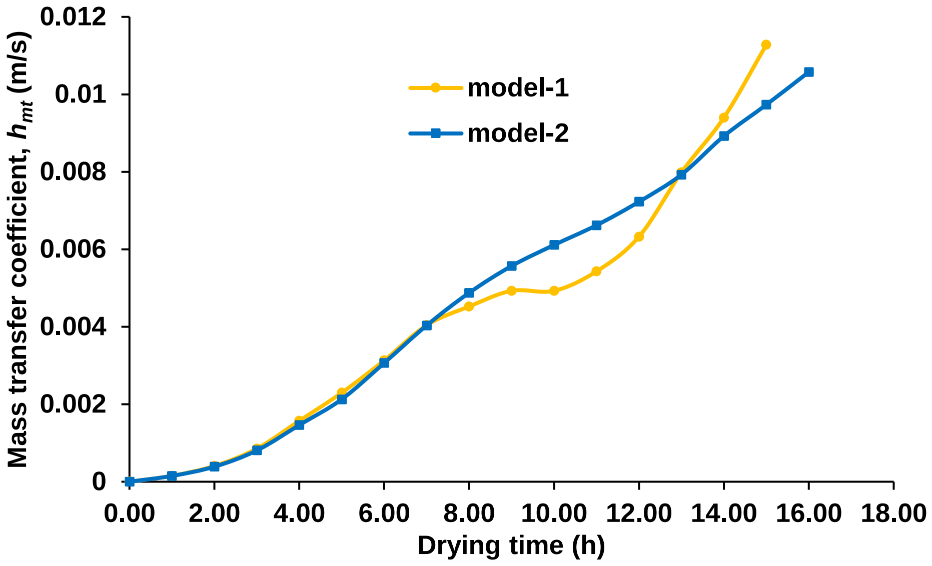
4.3.3.6. Mass and heat transfer coefficients (h_{mt} and h_{ht})

The h_{mt} and h_{ht} were evaluated in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli. During drying guava, the variation of h_{mt} and h_{ht} with drying time in model-1 and 2 is shown in **Fig. 4.30**. The variation of h_{mt} and h_{ht} with time are similar to the variation of D_{ef} as these parameters are directly proportional to D_{ef} (as mentioned in Eqs. 8 to 10). The values of h_{mt} of guava ranged from 0.153−11.28 × 10^{-3} m/s and 0.150–10.58 × 10^{-3} m/s in model-1 and 2, respectively. The h_{ht} range for the same was from 0.176 to 12.994 W/m^2K and 0.172 to 12.186 W/m^2K, respectively. The average h_{mt} of guava was found to be 4.20 × 10^{-3} and 4.68 × 10^{-3} m/s, in model-1 and 2, respectively. The average h_{ht} of guava was 4.842 and 5.394 W/m^2K in model-1 and 2, respectively. In model-2 compared to model-1, the average h_{mt} and h_{ht} of guava increased by 11.43 and 11.40%, respectively.

Similarly, during drying muskmelon, the h_{mt} values were in the range of 0.194−11.57 × 10^{-3} m/s and 0.178−9.42 × 10^{-3} m/s in model-1 and 2 respectively. The values of h_{ht} were in the range of 0.223−11.57 and 0.205−10.85 W/m^2K, respectively in model-1 and 2, respectively. The average h_{mt} of muskmelon was 4.36× 10^{-3} m/s in model-1 and in model-2, it was 4.55 × 10^{-3} m/s with an improvement of 4.36%. The increment in average h_{ht} was 4.28% in model-2 compared to model-1 with values of 5.026 and 5.241 W/m^2K in model-1 and 2, respectively. During drying beetroot, the h_{mt} was in the range of 0.081−10.22 × 10^{-3} m/s and 0.076−9.60 × 10^{-3} m/s, whereas, the h_{ht} was in the range of 0.093−11.77 W/m^2K and 0.088−11.06 W/m^2K, in model-1 and model-2, respectively. The average h_{mt} of beetroot increased by 2.25% in model-2 comparing with model-1 and it was 3.56 × 10^{-3} and 3.64 × 10^{-3} m/s, in model-1 and model-2, respectively. The average h_{ht} of beetroot increased by 2.19% in model-2 by comparing with model-2 and it was 4.103 and 4.193 W/m^2K in model-1 and 2, respectively.

During drying chilli, the h_{mt} was in the range of 0.082−10.12 × 10^{-3} m/s and 0.064−9.45 × 10^{-3} m/s, whereas, the h_{ht} was in the range of 0.095−11.66 W/m^2K and 0.074−10.89 W/m^2K, in model-1 and model-2, respectively. The average h_{mt} of chilli was found to be 3.71 × 10^{-3} and 3.81 × 10^{-3} m/s, in model-1 and 2, respectively. The average h_{ht} of chilli was 4.270 and 4.386 W/m^2K in model-1 and 2, respectively. In model-2 compared to model-1, the average h_{mt} and h_{ht} of chilli increased by 2.70 and 2.72%, respectively. The TES unit didn't make a major impact on these transfer coefficients because they are mainly depending on air velocity only. The estimated h_{mt} and h_{ht} in the present study are in a similar range available in the literature. The range of h_{mt} reported by Lingayat et al. [42] was 0.082−2.85 × 10^{-3} m/s for tomato slices. Chandramohan and Talukdar [126] obtained the average h of potato slices and it was 8.19 W/m^2K.

(a)



(b)

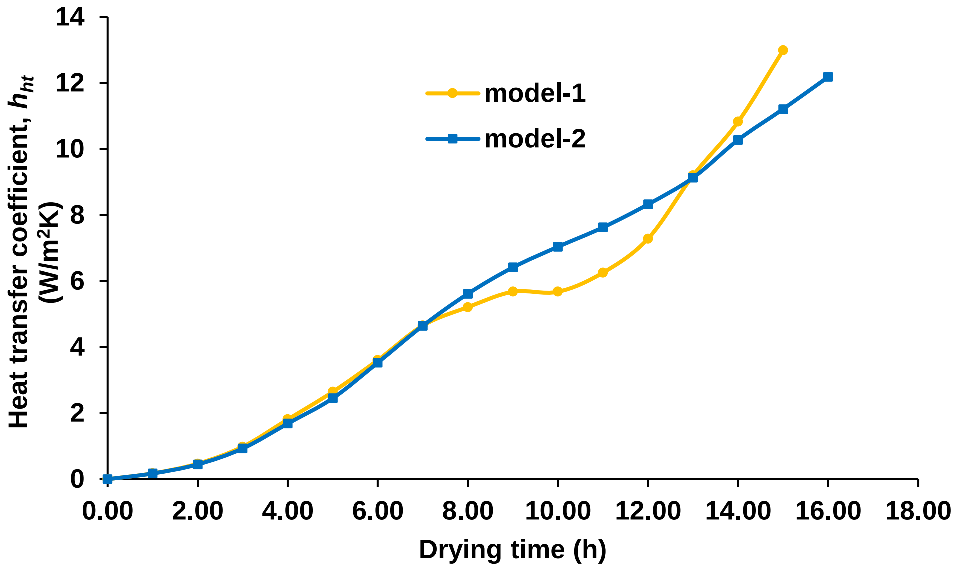


Fig. 4.30. Variation of (a) h_{mt} and (b) h_{ht} with time in model-1 and 2 during drying guava

4.3.3.7. Activation energy (E_{ac})

The E_{ac} was calculated by finding the slope of the linear curve between *ln* (D_{ef}) and (1/*T*+273.15) in model-1 and 2 during drying guava, muskmelon, beetroot and chilli. During drying guava, the E_{ac} was 116.49 and 110.38 kJ/mol in model-1 and model-2, respectively. When comparing model-2 to model-1, there is a 5.25% decrease in E_{ac} of guava due to higher MC removal at constant T_{dc} in model-2. Similarly, the E_{ac} of muskmelon was 28.61and 21.49 kJ/mol in model-1 and model-2, which is a 24.89% decrease. The E_{ac} of beetroot was 23.22 and 20.45 kJ/mol in model-1 and model-2, which is a 11.93% decrease. The E_{ac} of beetroot was 30.37 and 22.25 kJ/mol in model-1 and model-2, which is a 26.74% decrease. According to the literature, the calculated E_{ac} values were within a similar range of 12.76 to 73.38 kJ/mol for garlic cloves [13] and 4.41 to 95.17 kJ/mol for tomato slices [127].

4.3.4. Energy and exergy analysis

4.3.4.1. Energy analysis

Useful heat supplied by collector ($\dot{Q}_{u,SAC}$)

The $\dot{Q}_{u,SAC}$ is determined in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli. The variation in $\dot{Q}_{u,SAC}$ with time in model-1 and model-2 during drying guava is shown in **Fig. 4.31**. As $\dot{Q}_{u,SAC}$ is directly proportional to solar intensity, the $\dot{Q}_{u,SAC}$ is increased till noon and decreased afterward. During drying guava, the $\dot{Q}_{u,SAC}$ was in the range of 217.08 to 1809 W and 231.55 to 1837.94 W in model-1 and model-2, respectively. During drying guava, the average $\dot{Q}_{u,SAC}$ was 991.33 and 1034.02 W in model-1 and model-2, respectively. The $\dot{Q}_{u,SAC}$ was almost the same in both models because of similar average radiation data on successive days. The TES does not influence the $\dot{Q}_{u,SAC}$ since it is installed after the SAC outlet. Similarly, during drying muskmelon, the average $\dot{Q}_{u,SAC}$ was 981.23 and 1011.05 W in model-1 and model-2, respectively. During drying beetroot, the average $\dot{Q}_{u,SAC}$ was 1065.45 and 1084.8 W in model-1 and model-2, respectively. During drying chilli, the average $\dot{Q}_{u,SAC}$ was 1063.6 and 1060.13 W in model-1 and model-2, respectively.

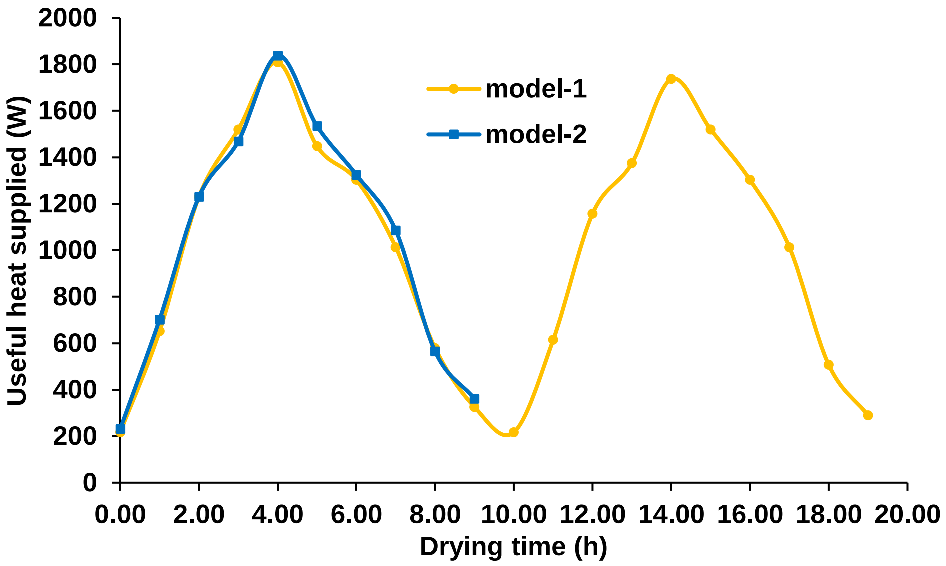


Fig. 4.31. Variation of useful heat supplied by SAC with time in model-1 and model-2 during drying guava

Collector efficiency ($\eta_{en,SAC}$)

The $\eta_{en,SAC}$ is determined in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli. The change in $\eta_{en,SAC}$ with time in model-1 and model-2 during drying guava is shown in **Fig. 4.32.** During drying guava, the $\eta_{en,SAC}$ is ranged from 36.16 to 86.87% (average of 65.37%) and 39.11 to 89.51 (average of 67.52%) in model-1 and model-2, respectively. The average $\eta_{en,SAC}$ was almost the same in both models due to similar weather conditions and the TES device does not affect the $\eta_{en,SAC}$. Similarly, during drying muskmelon, the range of $\eta_{en,SAC}$ was 35.64−89.09% (average of 66.37%) and 36.22−85.7% (average of 67.82) in model-1 and model-2, respectively. During drying beetroot, the $\eta_{en,SAC}$ is ranged from 36.12−87.91% (average of 71.09%) and 44.23−86.91% (average of 72.61%) in model-1 and model-2, respectively. During drying chilli, the range of $\eta_{en,SAC}$ was 46.73−89.60 (average of 74.24%) and 45.94−89.94% (average of 72.37%) in model-1 and model-2, respectively. A similar range of $\eta_{en,SAC}$ was reported in the ISDs by Nabnean et al. [61] (21 to 69%) and Arun et al. [128] (53.9 to 65.5%) while drying tomatoes and bananas, respectively.

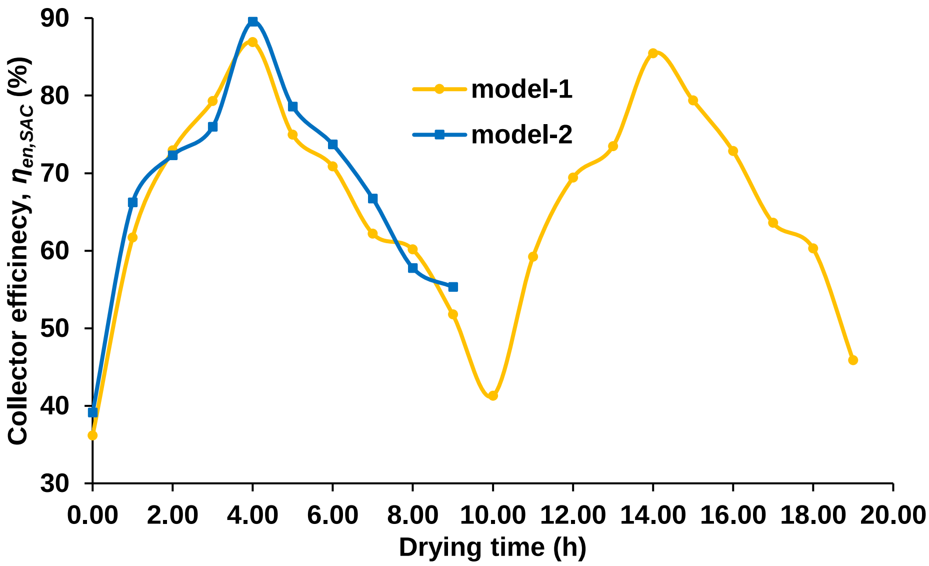


Fig. 4.32. Change in $\eta_{en,SAC}$ with time in model-1 and model-2 during drying guava

Drying efficiency ($\eta_{en,dry}$)

The $\eta_{en,dry}$ was estimated in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli.. The change in $\eta_{en,dry}$ with time in model-1 and model-2 during drying guava is shown in **Fig. 4.33.** While drying guava, average value of $\eta_{en,dry}$ in model-1 and 2 was found to be 10.26 and 14.66%, respectively. During drying guava, the average $\eta_{en,dry}$ was increased by 42.88% in model-2 compared to model-1. The average $\eta_{en,dry}$ is higher in model-2 since the guava slices were dried after the sunset due to the release of heat from PCM and the final MC is reached within a day. It is noticed that after 2.00 pm (6.00 h in X-axis), the $\eta_{en,dry}$ was higher in model-2 compared to model-1 due to constant T_{dc} could be maintained. Similarly, during drying muskmelon, the average $\eta_{en,dry}$ was 11.37 and 16.93% in model-1 and model-2, which is a 48.90% increase. Similarly, during drying beetroot, the average $\eta_{en,dry}$ was 11.31 and 16.81% in model-1 and model-2, which is a 48.63% increase. Similarly, during drying chilli, the average $\eta_{en,dry}$ was 11.80 and 17.03% in model-1 and model-2, which is a 44.32% increase. In the literature, a similar range of values was estimated by Cetina-Quinones et al. [57] (8.32 to 12.57%) in ISD with limestone during drying tomato slices and Andharia et al. [129] (6.8 to 10.61%) in ISD with paraffin wax during drying gooseberry slices.

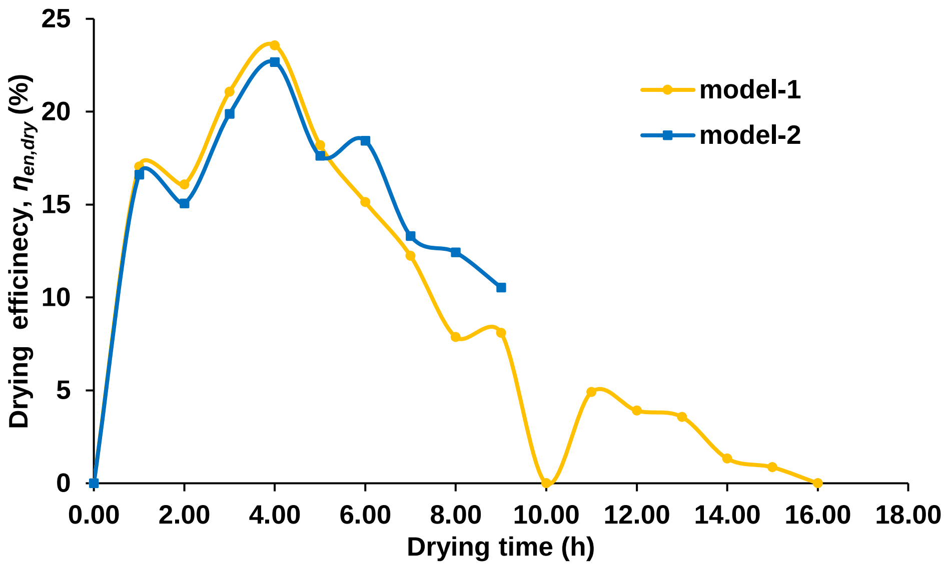


Fig. 4.33. Change in drying efficiency with time in model-1 and model-2 during drying guava

Specific energy consumption (SEC)

The SEC is estimated in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli. During drying guava, the SEC was obtained to be 1.675 and 1.029 kWh/kg in model-1 and model-2, respectively. The input energy in model-1 was solar radiation of two days but in model-2 it was solar radiation of one day. So, the SEC is decreased by 38.57% in model-2 compared to model-1 during drying guava. Similarly, during drying muskmelon, beetroot and chilli, the SEC was obtained to be 1.612 and 0.926 kWh/kg, 1.706 and 0.960 kWh/kg, 1.641 and 0.955 kWh/kg, in model-1 and model-2, respectively. In model-2 compared to model-1, the SEC was decreased by 42.56%, 43.73% and 41.80% during drying muskmelon, beetroot and chilli. The values of S_{EC} are lower than studies with TES reported in the literature: Kondareddy et al. [130] reported the SEC of 0.438 kWh/kg during drying elephant apple slices and Shanmugam and Natarajan [131] reported SEC of 1.818 kWh/kg during drying green peas.

Specific moisture extraction rate (SMER)

The SMER is a reciprocal of SEC and it is found to be higher in model-2 compared to model-1 during drying guava, muskmelon, beetroot and chilli. During drying guava, the SMER was found to be 0.597 and 0.972 kg/kWh in model-1 and model-2, which is a 62.81% increase. Since drying was completed in one day using lower quantity of input energy in model-2, the SMER is found to be higher in model-2 compared to model-1. Similarly, during drying muskmelon, beetroot and chilli, the SMER was found to be 0.620 and 1.080 kg/kWh, 0.586 and 1.041 kg/kWh, 0.609 and 1.047 kg/kWh, in model-1 and model-2, respectively. In model-2 compared to model-1, the SMER was increased by 74.19%, 77.65% and 71.92% during drying muskmelon, beetroot and chilli, respectively. The present setup gave higher SMER values compared to the existing studies done by Cetina-Quinones et al. [57] (0.196 kg/kWh for tomato slices) and Zachariah et al. [132] (0.28 kg/kWh for bitter gourd slices). Both studies used TES in their respective dryers.

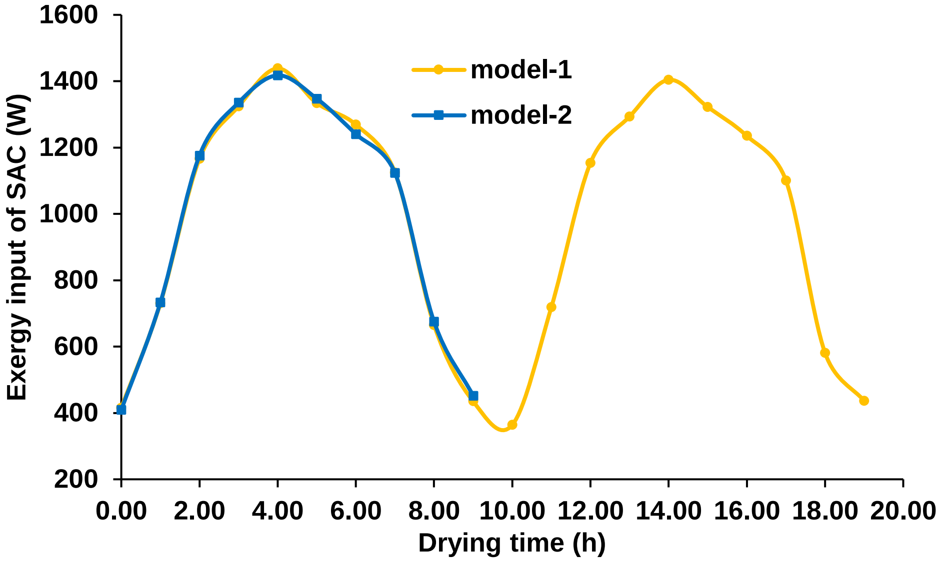
4.3.4.2. Exergy analysis

Exergy input, output and loss of the SAC

The exergy results (exergy input, output and loss) of SAC were determined during drying guava, muskmelon, beetroot and chilli in model-1 and model-2. The variation of $\dot{E}x_{in,SAC}$ with time in model-1 and model-2 during drying guava is shown in **Fig. 4.34 (a).** Similar to all other solar dependent parameters, $\dot{E}x_{in,SAC}$ for the setup with TES (model-2) was evaluated for one-day sunshine drying hours, while two days sunshine hours for the setup without TES (model-1). Maximum values of $\dot{E}x_{in,SAC}$ were noticed at noon when the highest solar intensity was supposed to be attained. The minimum, average and maximum $\dot{E}x_{in,SAC}$ in model-1 were evaluated to be 363.97, 975.57 and 1438.40 W and the same values in model-2 were 409.57, 990.97 and 1417.55 W, respectively. There was no significant variation noticed between the $\dot{E}x_{in,SAC}$ of the two setups. Similarly, $\dot{E}x_{ls,SAC}$ was evaluated from the temperature and solar data recorded during the drying experiment. The plot is not shown here for its similarity to the graph of $\dot{E}x_{in,SAC}$. The minimum, average and maximum $\dot{E}x_{ls,SAC}$ were 362.19, 947.27, 1364.67 W (model-1) and 408.29, 961.93 and 1346.06 W (model-2), respectively. The $\dot{E}x_{out,SAC}$ of model-1 and model-2 was evaluated with time and is described in **Fig. 4.34 (b).** From **Fig. 4.34 (b)**, the maximum $\dot{E}x_{out,SAC}$ is achieved at noon. The trend of variation was observed to be increasing with an increasing rate before the maximum value was attained, and then gradually started to decline with the solar intensity. This is because $\dot{E}x_{out,SAC}$ is dependent on the temperature of ambient air, collector outlet and inlet. Slight variations were observed in the values of $\dot{E}x_{out,SAC}$ between the two setups. This could be because of variation in the temperature of ambient air. The minimum, average and maximum $\dot{E}x_{out,SAC}$ in model-1 were evaluated to be 1.07, 28.30, and 73.73 W and the same values in model-2 were 1.28, 29.03 and 71.49 W, respectively.

Similarly, during drying muskmelon, the average exergy input, output and loss of collector in model-1 were 952.91, 27.67 and 925.25 W and the same values in model-2 were 963.57, 29.80 and 933.78 W, respectively. During drying beetroot, the same were 974.78, 32.07 and 942.71 W (model-1) and 980.15, 31.68 and 948.47 W (model-2), respectively. During drying chilli, the same were 941.70, 31.84 and 909.85 (model-1) and 959.19, 31.37 and 927.82 (model-2), respectively.

(a)



(b)

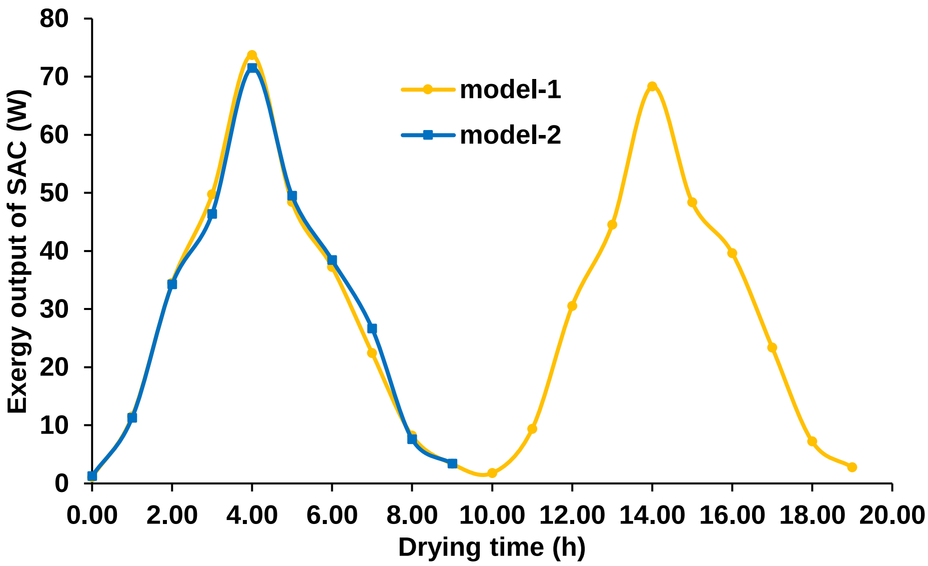


Fig. 4.34. Exergy (a) input and (b) output of SAC in model-1 and 2 during drying guava

Exergy efficiency of the SAC *($\eta_{ex,SAC}$)*

The $\eta_{ex,SAC}$ for model-1 and model-2 during drying guava, muskmelon, beetroot and chilli has been evaluated and its variation with time during drying guava is described in **Fig. 4.35**. The exergy input and output directly influence the exergy efficiency. Moreover, solar radiation is one of the key influencing factors of $\dot{Ex}_{in,SAC}$ which indirectly determines the exergy efficiency. During drying guava, based on the corresponding values of 0.26–5.13 % and 0.31–5.04 %, the average $\eta_{ex,SAC}$ for model-1 and model-2 was 2.39 and 2.43 %, respectively. The similar conditions of weather on successive days resulted in almost the same $\eta_{ex,SAC}$ in both models and the effect of the TES device is not there on the value of $\eta_{ex,SAC}$. Similarly, during drying muskmelon, beetroot and chilli, the $\eta_{ex,SAC}$ was found to be 2.43 and 2.57 %, 2.80 and 2.76 %, 2.85 and 2.78, in model-1 and model-2, respectively. The values of $\eta_{ex,SAC}$ of present setups are almost similar to the values specified by Abdelkader et al. [133] (0.27 and 6.6%) and by Abuska et al. [134] (1 to 7%).

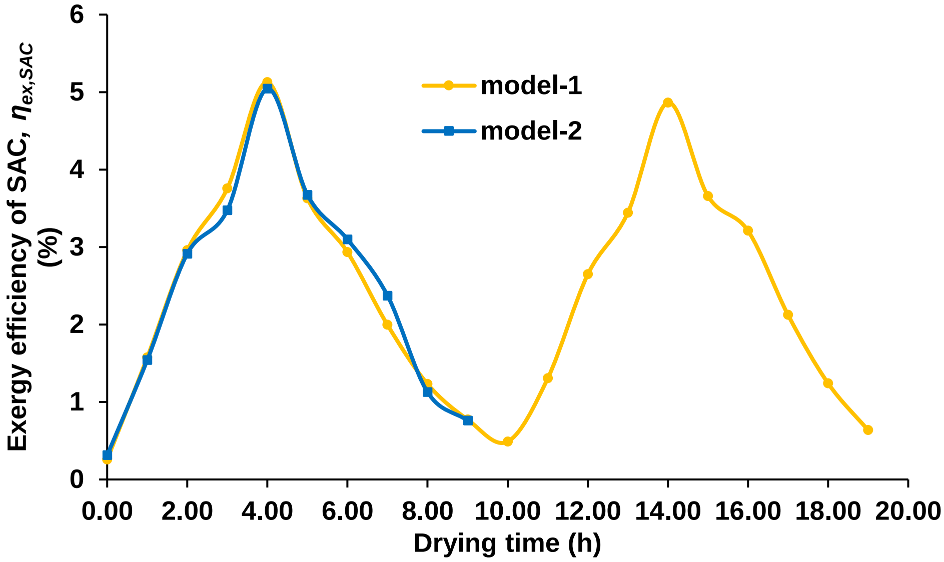


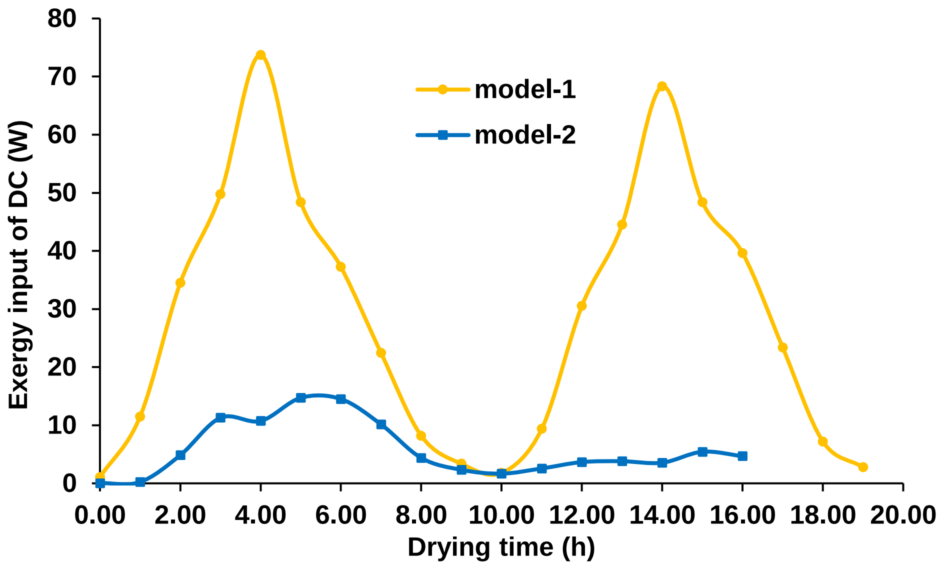
Fig. 4.35. Variation of $\eta_{ex,SAC}$ with time in model-1 and 2 during drying guava

Exergy input, output and loss of the drying chamber

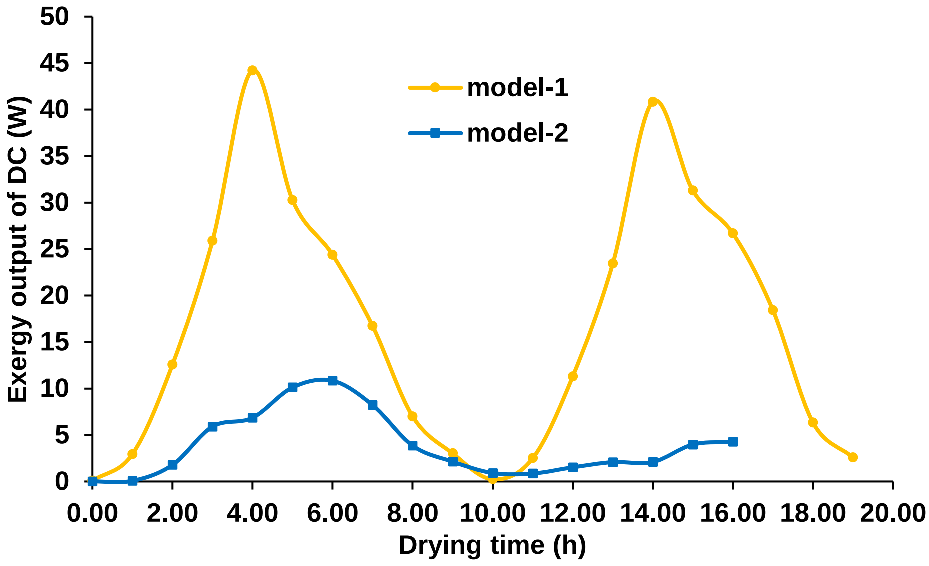
The exergy results (exergy input, output and loss) of drying chamber were determined in model-1 and 2 during drying guava, muskmelon, beetroot and chilli and the graph of guava is shown in **Fig. 4.36**. As indicated in the mentioned **Fig. 4.36 (a),** the $\dot{E}x_{in,dc}$ was seen to be varied similar to the trend of solar radiation variation for both models. In model-2, the $\dot{E}x_{in,dc}$ values are lower in sunshine hours compared to model-1 because TES absorbs the thermal energy and T_{dci} is decreased in model-2. For model-2, however, $\dot{E}x_{in,dc}$ was almost constant after sunset because the TES device sustains the temperature by discharging the thermal energy stored during sunshine hours. During drying guava, the average values of $\dot{E}x_{in,dc}$ for model-1 and model-2 were 28.30 and 5.80 W, and their corresponding ranges were 1.07−73.73 W and 0.04−14.72 W, respectively. During drying guava, the $\dot{E}x_{out,dc}$ was evaluated and described in **Fig. 4.36 (b).** It is a function of the T_{dco} and atmospheric temperature. The average values of $\dot{E}x_{out,dc}$ for the model-1 and model-2 were 16.54 and 3.85 W, respectively. Its estimated ranges of values for the same were 0.08–44.22 W and 0.01–10.83 W, respectively. During drying guava, the $\dot{E}x_{ls,dc}$ was determined and shown in **Fig. 4.36 (c).** The $\dot{E}x_{ls,dc}$ is determined from exergy balance and it is equal to the difference in exergy input and output of the drying chamber. The values of $\dot{E}x_{ls,dc}$ were found to be lower in model-2 compared to model-1 due to constant T_{dc} could be maintained in model-2. The average values of $\dot{E}x_{ls,dc}$ for model-1 and model-2 were 11.76 and 1.95 W, and their corresponding ranges were 0.19−29.51 W and 0.04−5.38 W, respectively.

Similarly, during drying muskmelon, the average exergy input, output and loss of drying chamber in model-1 were 27.67, 16.17 and 11.50 W and the same values in model-2 were 6.32, 4.31 and 2 W, respectively. During drying beetroot, the same were 32.07, 18.66 and 13.41 W (model-1) and 7.86, 5.10 and 2.77 W (model-2), respectively. During drying chilli, the same were 31.84, 19.32 and 12.53 (model-1) and 8.12, 5.46 and 2.67 (model-2), respectively.

(a)



(b)



(c)

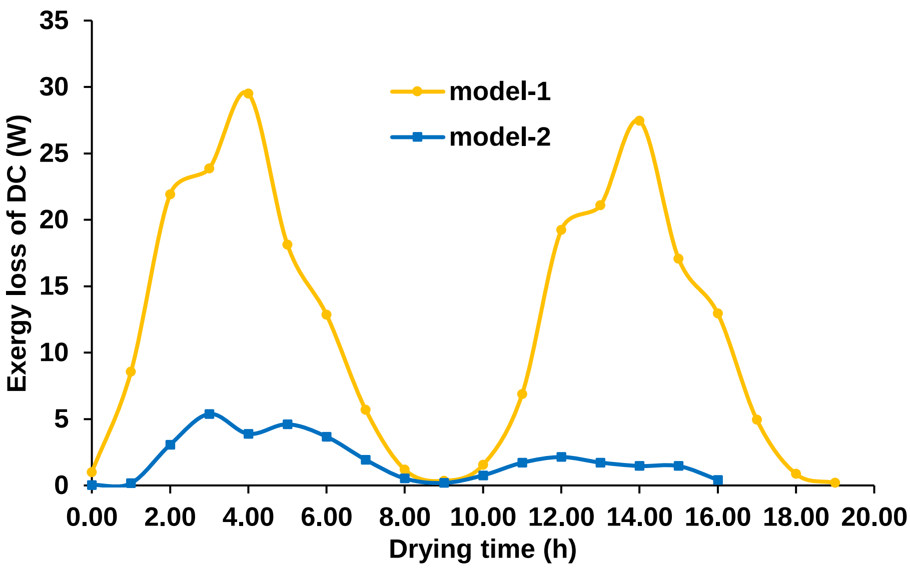


Fig. 4.36. Exergy (a) input (b) output and (c) loss of drying chamber with time in model-1 and 2 during drying guava

Exergy efficiency of the drying chamber ($\eta_{ex,dc}$)

The change of $\eta_{ex,dc}$ with drying time in model-1 and model-2 is determined during drying guava, muskmelon, beetroot and chilli and its variation with time during drying guava is shown in **Fig. 4.37**. It is observed that as time increases, $\eta_{ex,dc}$ also increases in both models. It is noticed that higher values of $\eta_{ex,dc}$ are observed in model-2 compared to model-1 because the constant T_{dc} is maintained by TES in model-2 from noon to sunset. The evaluated values of $\eta_{ex,dc}$ for model-1 and model-2 were in the range of 7.21−93.23% and 17.46−91.87% and the averages were 57.03 and 59.46%, respectively. The model-2 showed an improvement of 4.09 % of $\eta_{ex,dc}$ of the drying section compared to the model-1during drying guava. Similarly, during drying muskmelon, beetroot and chilli, the average $\eta_{ex,dc}$ was found to be 55.73 and 62.27%, 54.92 and 60.70%, 56.23 and 60.20%, in model-1 and model-2, respectively. In model-2 compared to model-1, the average $\eta_{ex,dc}$ was improved by 11.74%, 10.52% and 7.06% during drying muskmelon, beetroot and chilli, respectively. The $\eta_{ex,dc}$ values were similar to the range reported in solar dryers with TES from the literature: orange (54.71−68.37%) [121], ghost chilli (21−98%) [120], bitter gourd (8.66−79.02%) [111] and carrot (42−91%) [125].

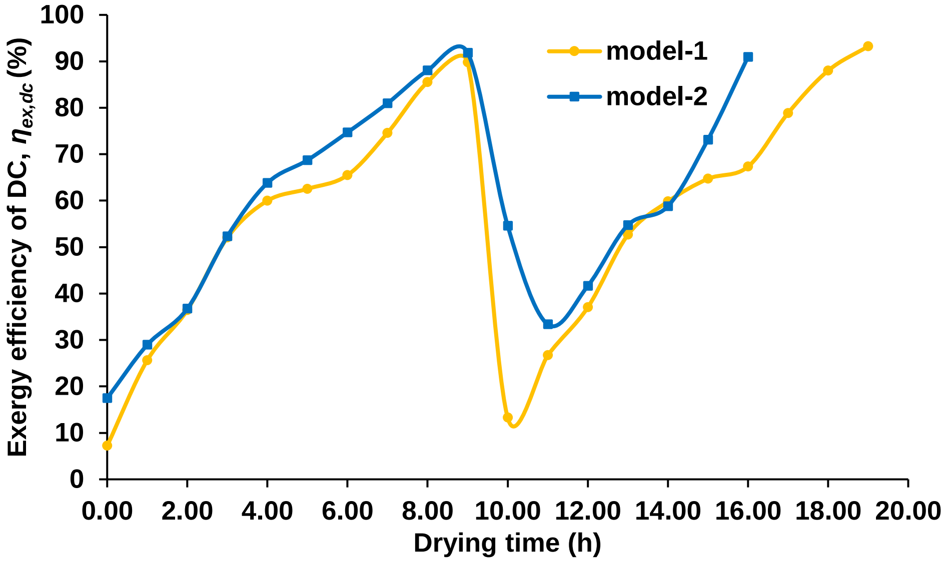


Fig. 4.37. The change of $\eta_{ex,dc}$ with time during drying guava in model-1 and 2

Exergy sustainability indicators

The exergy sustainability indicators such as IP, EIF, WER and SI are evaluated during drying guava, muskmelon, beetroot and chilli in model-1 and model-2. They were estimated to figure out the exergy efficiency and exergy loss of the drying section with the reference to exergy input. The variation of IP and EIF with drying time in model-1 and model-2 during drying guava is shown in **Fig. 4.38**. The IP and EIF values were found to be lower in model-2 compared to model-1 because of lower exergy loss due to the constant T_{dc} by TES in model-2. The variation of SI and WER with time during drying guava is described in **Fig. 4.39.** The WER values are lower in model-2 compared to model-1 due to lower exergy loss and it decreases with time. The SI values are directly proportional to exergy efficiency and found to be higher in model-2 compared to model-1. It is concluded that IP, EIF and WER are directly proportional to exergy loss and SI is inversely proportional to exergy loss of drying chamber.

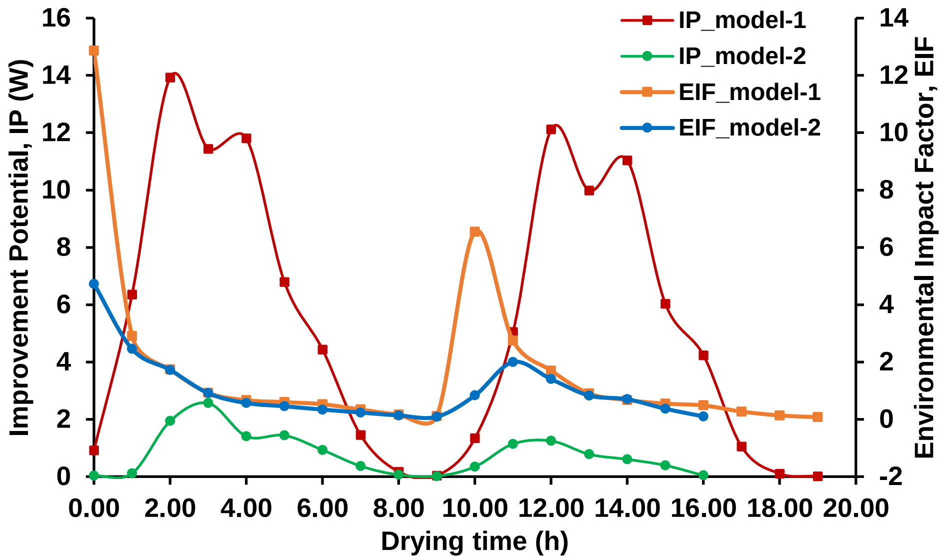


Fig. 4.38. Change in IP and EIF with time during drying guava in model-1 and 2

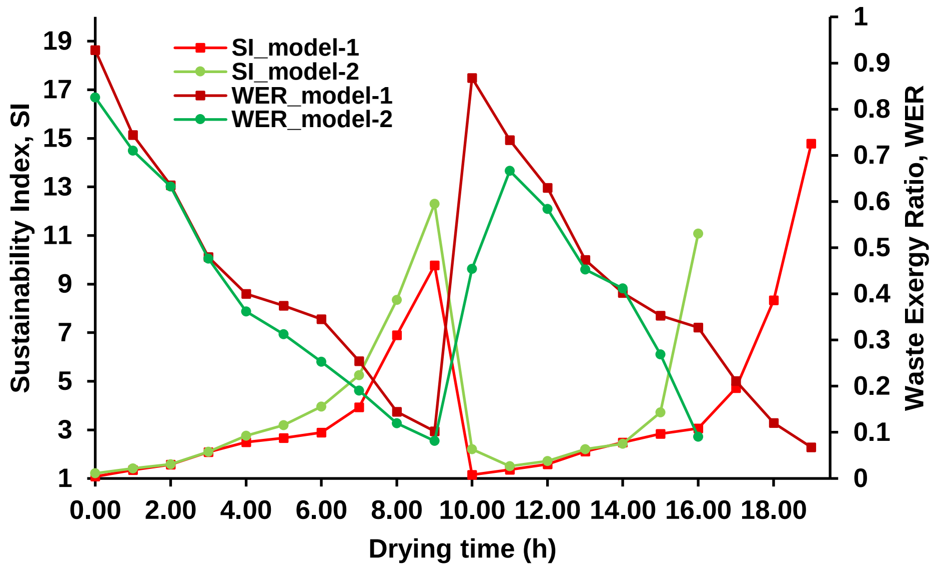


Fig. 4.39. Variation of SI and WER with time during drying guava in model-1 and 2

In **Table 4.11,** the ranges and averages of IP, EIF, WER and SI in model-1 and model-2 during drying guava, muskmelon, beetroot and chilli were mentioned**.** The results of the present study are in good agreement with the existing literature (**Table 4.11**). The average value of IP, EIF and WER were decreased by 85.40%, 39.66% and 4.65%, and SI was increased by 2.07% in model-2 compared to model-1 during drying guava due to lower exergy losses in model-2.

Similar observations were noticed during drying muskmelon, beetroot and chilli. The higher value of SI and lower values of IP, EIF and WER indicate that the exergetic performance of FCISD is enhanced by TES device compared to without TES device.

Table 4.11. Values of exergy sustainability indicators in FCISD without and with TES device

Indicator	Sample	FCISD without TES (model-1)		FCISD with TES (model-2)		Literature
		Range	Avg.	Range	Avg.	
IP (W)	Guava	0.01−11.8	5.41	0.02−2.56	0.79	0.04−20.6 W [122], 0.24−7.92 W [111]
	Muskmelon	0.01−11.35	5.37	0.01−2.91	0.85	
	Beetroot	0.06−14.88	6.17	0.02−2.85	1.18	
	Green chilli	0.05−12.81	5.52	0.06−2.74	1.09	
EIF	Guava	0.07−12.87	1.75	0.09−4.73	1.05	0.16−2.4 [84], 11.28−40.35 [13]
	Muskmelon	0.07−7.90	1.79	0.04−6.07	1.06	
	Beetroot	0.14−14.20	2.07	0.06−10.70	1.34	
	Green chilli	0.12−7.72	1.72	0.08−5.73	1.14	
WER	Guava	0.07−0.93	0.43	0.08−0.83	0.41	0.63−0.81 [64], 0.15−0.34 [124]
	Muskmelon	0.06−0.88	0.44	0.04−0.86	0.38	
	Beetroot	0.12−0.93	0.45	0.05−0.91	0.39	
	Green chilli	0.11−0.89	0.44	0.08−0.85	0.40	
SI	Guava	1.08−14.78	3.86	1.21−12.30	3.94	0.39−6.16 [84], 2.39−6.11 [122]
	Muskmelon	1.12−14.78	3.68	1.16−25.02	5.63	
	Beetroot	1.07−8.06	3.06	1.09−18.69	4.29	
	Green chilli	1.13−9.32	3.43	1.17−13.25	3.95	

4.3.5. Summary of results in FCISD without and with TES

The drying kinetics and energy and exergy analysis of FCISD without TES (model-1) and with TES (model-2) are compared and assessed. The values of different parameters found in model-1 and model-2 without TES and their increment/decrement with respect to model-1 during drying guava, muskmelon, beetroot and green chilli are summarised in **Table 4.12.** The drying kinetics such as MC, DR, D_{ef}, h_{mt}. h_{ht} and E_{ac} were found in both models. The drying models were evaluated to describe the drying characters of guava, muskmelon, beetroot and green chilli in both models. In the energy and exergy analysis, parameters such as $\eta_{en,SAC}$, $\eta_{en,dry}$, SEC, SMER, $\eta_{ex,SAC}$, $\eta_{ex,dc}$, IP, EIF, WER and SI were found in both models.

The average DR, D_{ef}, h_{mt}, h_{ht}, $\eta_{en,dry}$, $\eta_{ex,dc}$ and SI are higher in model-2 compared to model-1 due to constant drying air temperature was maintained as the heat absorbed and released by TES in model-2 and drying was completed in one day. The other parameters such as average E_{ac}, SEC, IP, EIF and WER are lower in model-2 compared to model-1. The average $\eta_{en,SAC}$ and $\eta_{ex,SAC}$ were almost the same in both models due to similar weather conditions and the TES device does not affect the performance of collector as TES is installed in the drying chamber. In model-1, the Page, Two-term exponential, Two-term exponential and Two-term exponential models were best suited models to describe drying curves of guava, muskmelon, beetroot and green chilli, respectively. In model-2, the best suited models for the samples were Page, Page, Page and modified Page model, respectively. The drying duration in sunshine hours was reduced by 5 h for guava and 6 h for muskmelon, beetroot and green chilli in model-2 compared to model-1. In model-2, all samples were dried for 7 non-shine hours from 5.00 pm to midnight. From **Table 4.12**, it implies that the TES device enhances the performance and efficiency of the FCISD setup since it keeps the T_{dc} constant in afternoon and higher MC is removed with a lower input energy.

Table 4.12. Results comparison of FCISD without and with TES device

Parameter (average)	**Sample**	**FCISD without TES (model-1)**	**FCISD with TES (model-2)**	**% increase/decrease**
Final MC (db)	Guava	0.0244	0.0342	-
	Muskmelon	0.1605	0.2108	-
	Beetroot	0.0569	0.0767	-
	Green chilli	0.1137	0.1513	-
Drying duration, sunshine hours (h)	Guava	14	9	35.71 (decrease)
	Muskmelon	15	9	40.00 (decrease)
	Beetroot	15	9	40.00 (decrease)
	Green chilli	15	9	40.00 (decrease)
	Guava	0.3936	0.5728	45.53 (increase)

DR (kg/h)	Muskmelon	0.8170	1.2585	54.04 (increase)
	Beetroot	0.5131	0.7268	41.65 (increase)
	Green chilli	0.5523	0.7661	38.71 (increase)
D_{ef} (m^2/s)	Guava	7.98×10^{-9}	8.63×10^{-9}	8.15 (increase)
	Muskmelon	3.04×10^{-8}	3.13×10^{-8}	2.96 (increase)
	Beetroot	7.11×10^{-9}	7.22×10^{-9}	1.55 (increase)
	Green chilli	1.68×10^{-9}	1.71×10^{-9}	1.79 (increase)
h_{mt} (m/s)	Guava	4.20×10^{-3}	4.68×10^{-3}	11.43 (increase)
	Muskmelon	4.36×10^{-3}	4.55×10^{-3}	4.36 (increase)
	Beetroot	3.56×10^{-3}	3.64×10^{-3}	2.25 (increase)
	Green chilli	3.71×10^{-3}	3.81×10^{-3}	2.70 (increase)
h_{ht} (W/m^2K)	Guava	4.842	5.394	11.40 (increase)
	Muskmelon	5.026	5.241	4.28 (increase)
	Beetroot	4.103	4.193	2.19 (increase)
	Green chilli	4.270	4.386	2.72 (increase)
E_{ac} (kJ/mol)	Guava	116.49	110.38	5.25 (decrease)
	Muskmelon	28.61	21.49	24.89 (decrease)
	Beetroot	23.22	20.45	11.93 (decrease)
	Green chilli	30.37	22.25	26.74 (decrease)
$\eta_{en,SAC}$ (%)	Guava	65.37	67.52	constant
	Muskmelon	66.37	67.82	constant
	Beetroot	71.09	72.61	constant
	Green chilli	74.24	72.37	constant
$\eta_{en,dry}$ (%)	Guava	10.26	14.66	42.88 (increase)
	Muskmelon	11.37	16.93	48.90 (increase)
	Beetroot	11.31	16.81	48.63 (increase)
	Green chilli	11.80	17.03	44.32 (increase)
SEC (kWh/kg)	Guava	1.675	1.029	38.57 (decrease)
	Muskmelon	1.612	0.926	42.56 (decrease)
	Beetroot	1.706	0.960	43.73 (decrease)
	Green chilli	1.641	0.955	41.80 (decrease)
	Guava	0.597	0.972	62.81 (increase)

SMER (kg/kWh)	Muskmelon	0.620	1.080	74.19 (increase)
	Beetroot	0.586	1.041	77.65 (increase)
	Green chilli	0.609	1.047	71.92 (increase)
$\eta_{ex,SAC}$ (%)	Guava	2.39	2.43	constant
	Muskmelon	2.43	2.57	constant
	Beetroot	2.80	2.76	constant
	Green chilli	2.85	2.78	constant
$\eta_{ex,dc}$ (%)	Guava	57.03	59.46	4.09 (increase)
	Muskmelon	55.73	62.27	11.74 (increase)
	Beetroot	54.92	60.70	10.52 (increase)
	Green chilli	56.23	60.20	7.06 (increase)
IP (W)	Guava	5.41	0.79	85.40 (decrease)
	Muskmelon	5.37	0.85	84.17(decrease)
	Beetroot	6.17	1.18	80.88 (decrease)
	Green chilli	5.52	1.09	80.25 (decrease)
EIF	Guava	1.75	1.05	39.66 (decrease)
	Muskmelon	1.79	1.06	40.78(decrease)
	Beetroot	2.07	1.34	35.27 (decrease)
	Green chilli	1.72	1.14	33.72 (decrease)
WER	Guava	0.43	0.41	4.65 (decrease)
	Muskmelon	0.44	0.38	13.64(decrease)
	Beetroot	0.45	0.39	13.33 (decrease)
	Green chilli	0.44	0.40	9.09 (decrease)
SI	Guava	3.86	3.94	2.07 (increase)
	Muskmelon	3.68	5.63	52.99 (increase)
	Beetroot	3.06	4.29	40.20 (increase)
	Green chilli	3.43	3.95	15.16 (increase)

4.4. Uncertainty values of parameters

The uncertainty values of parameters measured and estimated during drying experiments of guava, muskmelon, beetroot and green chilli were found by root sum square method [59] and average values are summarised in **Table 4.13**.

Table 4.13. Uncertainties of parameters during experimentation

Parameter	Uncertainty
Solar radiation	± 10 W/m^2
Air temperature	± 1 °C
Velocity of air	± 0.03 m/s
Relative humidity of air	± 2%
Mass of the food product	± 0.0002 g
Moisture content	± 0.0235 kg per kg of db
Drying rate	± 0.019 kg/h
Moisture ratio	± 0.0132
Effective diffusion coefficient	± 1.52×10^{-10} m^2/s
Mass transfer coefficient	± 1.62×10^{-4} m/s
Heat transfer coefficient	± 0.0575 W/m^2K
Activation energy	± 2.24 kJ/mol
Useful heat supplied	± 21.54 W
Collector efficiency	± 1.32 %
Drying efficiency	± 0.72%
Specific energy consumption	± 0.0365 kWh/kg
Specific moisture extraction rate	± 0.0172 kWh/kg
Exergy input, output and loss of the collector	± 23, ± 0.75 and ± 19 W
Exergy input, output and loss of drying chamber	± 0.75, ± 0.29 and ± 0.46 W
Exergy efficiency of collector and drying chamber	± 0.052% and ± 1.27%
Improvement potential	± 0.39 W
Environmental impact factor	± 0.14 W
Waste exergy ratio	± 0.013
Sustainability index	± 0.45

Chapter 5

Conclusions

Chapter 5

5. Conclusions

In the present study, the drying experiments were conducted on natural convection indirect solar dryer (NCISD) and forced convection ISD (FCISD) for guava, muskmelon and beetroot. The trapezoidal duct consist of 3 DC fans powered by solar PV panels is attached at the entrance of the solar air collector (SAC) in NCISD to provide forced convection. In NCISD and FCISD, the drying experiments were conducted for two days from morning 8.00 am to evening 5.00 pm. The drying kinetics and energy and exergy analysis (EEA) of NCISD and FCISD were evaluated. A thermal energy storage (TES) device is developed to install it in the drying chamber of ISD. The TES device was fabricated that consist of 50 number of TES cells and installed in the drying chamber of ISD to store and release the thermal energy. Next, the drying experiments were conducted on FCISD without TES device (model-1) and with TES device (model-2) for guava, muskmelon, beetroot and green chilli. In model-2, the experiments were conducted for one day from morning 8.00 am to midnight 12.00 am. The drying kinetics and EEA of model-1 and model-2 were also evaluated.

During experimentation, mass of the samples, solar radiation, temperature, relative humidity and velocity of air were measured. The temperature distribution of air in ISD at various locations was analysed. The drying kinetics such as moisture content (MC), drying rate (DR), moisture ratio (MR), effective diffusion coefficient (D_{ef}), mass and heat transfer coefficients (h_{mt} and h_{ht}) and activation energy (E_{ac}) were evaluated during drying food products. The drying models from literature which represent MR vs time were evaluated for food products and best model to describe the experimental data of food products has been found. In the energy analysis, collector efficiency ($\eta_{en,SAC}$), drying efficiency ($\eta_{en,dry}$), specific energy consumption (SEC) and specific moisture extraction rate (SMER) were evaluated. In the exergy analysis, exergy input, output, loss and efficiency of the SAC and drying chamber were found. The exergy sustainability indicators such as improvement potential (IP), environmental impact factor (EIF), waste exergy ratio (WER) and sustainability index (SI) were determined.

Finally, parameters found in drying kinetics and EEA of NCISD and FCISD without TES device were summarised and compared. Also, the parameters found in drying kinetics and EEA of the model-1 and model-2 were summarised and compared. The main conclusions obtained from the present study were summarised in subsequent sections.

5.1. Drying kinetics in NCISD and FCISD without TES

Initially, the drying experiments of guava, muskmelon and beetroot were conducted on NCISD. Next, a trapezoidal duct consist of 3 DC fans powered by solar PV panels was added with the existing NCISD setup to conduct experiments on FCISD. The following conclusions were drawn from the drying kinetics of food products:

- The average collector outlet temperature (T_{co}) was found to be lower in FCISD compared to NCISD. The average temperature of drying chamber (T_{dc}) in NCISD and FCISD were 49.93 & 45.14 °C, 46.7 & 42.94 °C, 47.60 & 45.55 °C during drying guava, muskmelon and beetroot, respectively.
- The MC of guava reduced from 5.5355 kg/kg of dry basis (db) to 0.0244 db in 18 and 14 h in NCISD and FCISD, respectively. Similarly, MC of muskmelon was reduced from 12.4156 to 0.1605 db in 18 and 15 h, respectively. Similarly, MC of beetroot was reduced from 7.7535 to 0.0569 db in 18 and 15 h, respectively. The drying duration of 4, 3 and 3 h were reduced during drying guava, muskmelon and beetroot, respectively in FCISD.
- The quality of samples dried in ISD (either natural or forced) was found to be better compared to open sun drying (OSD).
- The average DR of guava, muskmelon and beetroot was found to be 0.3062 & 0.3936 kg/h, 0.6808 & 0.8170 kg/h and 0.4276 & 0.5131 kg/h, in NCISD and FCISD, respectively. The drying rate was improved in FCISD compared to NCISD due to enhanced mass flow rate of air in FCISD.
- Two-term exponential model was found to be best model to describe experimental data of guava in NCISD during drying guava, muskmelon and beetroot. Whereas Page model, Two-term exponential and Two-term exponential models were found to be best models in FCISD during drying guava, muskmelon and beetroot, respectively.
- In FCISD compared to NCISD, the average D_{ef}, h_{mt} and h_{ht} were increased by 34.12, 55.55 and 55.59% for guava, respectively. For muskmelon, the same were increased by 24.08, 55.16 and 55.36%, respectively. For beetroot, the same were increased by 20.30, 33.33 and 33.17%, respectively.

- The E_{ac} of guava, muskmelon and beetroot was found to be 136.98 & 116.49 kJ/mol, 38.06 & 28.61 kJ/mol, 27.57 & 23.22 kJ/mol, in NCISD and FCISD, respectively. In FCISD compared to NCISD, the E_{ac} values were lower due to higher amount of MC removal at higher mass flow rates in FCISD.

5.2. Energy and exergy analysis of NCISD and FCISD without TES

The drying experiments were conducted on NCISD and FCISD. Energy and exergy analysis was conducted in NCISD and FCISD during drying guava, muskmelon and beetroot and following conclusions were drawn:

- The $\eta_{en,SAC}$ was improved by 16.63, 13.45 and 8.34% during drying guava, muskmelon and beetroot in FCISD, respectively. Similarly, the $\eta_{en,dry}$ was also improved by 33.07, 21.09 and 19.18% during drying the same, respectively. The $\eta_{en,SAC}$ and $\eta_{en,dry}$ were noticed to be higher in FCISD compared to NCISD.
- In FCISD, the SEC of guava, muskmelon and beetroot were decreased by 20.54, 12.30 and 12.38%, respectively. Whereas the SMER for the same were increased by 25.95, 13.97 and 14.23%, respectively. Since lower amount of energy is needed to remove MC in FCISD compared to NCISD, the SEC values were lower and SMER values were higher in FCISD.
- The exergy efficiency of SAC ($\eta_{ex,SAC}$) was found to be lower in FCISD during drying guava, muskmelon and beetroot due to lower T_{co} in FCISD. The exergy efficiency of drying chamber ($\eta_{ex,dc}$) was enhanced by 11.99, 21.50 and 11.11% during drying guava, muskmelon and beetroot in FCISD due to lower temperature drop in drying chamber in FCISD.
- The average decrement of 52.46% on IP, 26.16% on EIF and 12.24% on WER, and average increment of 35.92% on SI were noticed in FCISD compared to NCISD during drying guava due to lower exergy losses in FCISD. Similar observations were noticed during drying muskmelon and beetroot.

5.3. Drying kinetics in FCISD without and with TES

The drying experiments were conducted on FCISD without TES device (model-1) and FCISD with TES device (model-2) during drying guava, muskmelon, beetroot and green chilli. The following conclusions were drawn for the drying kinetics in model-1 and model-2:

- The T_{dc} was maintained to be 2.5 to 8.5 °C higher than atmospheric temperature from 6.00 pm to midnight during drying guava, muskmelon, beetroot and chilli in model-2.
- The final MC reached in model-2 during drying guava, muskmelon, beetroot and green chilli were 0.0342, 0.2108, 0.0767 and 0.1513 db, respectively. The model-2 used 9 sunshine hours and 7 non-sunshine hours (total 16 hours) to reach final MC of food products. The model-1 used 14 sunshine hours for guava drying and 15 sunshine hours for muskmelon, beetroot and chilli drying.
- The quality of samples dried in both models was found to be same but better than the samples dried in OSD.
- The average DR was improved by 45.53, 54.04, 41.65, 38.71% during drying guava, muskmelon, beetroot and chilli, respectively, in model-2 compared to model-1.
- In model-1, the Page and Two-term exponential models were best suited models to describe drying curves of guava, muskmelon, beetroot and chilli, respectively. In model-2, the best suited models for the same were Page and modified Page model, respectively.
- In model-2 compared to model-1, the average D_{ef}, h_{mt} and h_{ht} were improved by 8.15, 11.43 and 11.40% for guava, respectively. Similarly, these were improved during drying muskmelon, beetroot and chilli in model-2. Minimal improvements in D_{ef}, h_{mt} and h_{ht} were noticed in model-2 since these were strong function of air velocity.
- The E_{ac} was decreased by 5.25, 24.89, 11.93 and 26.74% in model-2 during drying guava, muskmelon, beetroot and chilli, respectively, due to constant T_{dc} in model-2.

5.4. Energy and exergy analysis of FCISD without and with TES

The experiments were conducted on FCISD without (model-1) and with TES (model-2) during guava, muskmelon, beetroot and green chilli and major findings from energy and exergy analysis of model-1 and model-2 were:

- The average $\eta_{en,SAC}$ and $\eta_{ex,SAC}$ was almost the same in both models due to similar weather conditions and the TES device did not affect the performance of the collector as TES was installed in the drying chamber.
- The average $\eta_{en,dry}$ was improved by 42.88, 48.90, 48.63 and 44.32% in model-2 compared to model-1 during drying guava, muskmelon, beetroot and chilli,

respectively, because drying was completed in one day in model-2. Similarly, the $\eta_{ex,dc}$ was improved by 4.09, 11.74, 10.52 and 7.06% in model-2 for the same, respectively.

- The SEC of guava, muskmelon, beetroot and chilli was decreased by 38.57, 42.56, 43.73 and 41.80% in model-2 compared to model-1. The SMER for the same was increased by 62.81, 74.19, 77.65 and 71.92%, respectively. Since drying was completed in one day using lower quantity of input energy in model-2, the SEC was found to be lower and SMER was found to be higher in model-2 compared to model-1.
- During drying guava, muskmelon, beetroot and chilli in model-2, the exergy sustainability indicators such as IP, EIF, WER were decreased by 80.25−85.40%, 33.72−39.66% and 4.65−13.64%, respectively. Whereas, for the same samples, the SI was increased by 2.07−52.99% in model-2 compared to model-1. The lower exergy losses and maintenance of constant T_{dc} improved the sustainability indicators in model-2.

5.5. Overall conclusions

- The averages of DR, D_{ef}, h_{mt}, h_{ht}, $\eta_{en,SAC}$, $\eta_{en,dry}$, $\eta_{ex,dc}$ and SI were higher, and the averages of T_{co}, T_{dc}, E_{ac}, SEC, $\eta_{ex,SAC}$, IP, EIF and WER were lower in FCISD compared to NCISD without TES.
- The averages of DR, D_{ef}, h_{mt}, h_{ht}, $\eta_{en,dry}$, $\eta_{ex,dc}$ and SI were higher, and averages of E_{ac}, SEC, IP, EIF and WER were lower in FCISD with TES device compared to without TES device. The averages of $\eta_{en,SAC}$ and $\eta_{ex,SAC}$ were almost the same in both models.
- The drying duration was reduced by 3 to 4 h in FCISD compared to NCISD. The drying duration was reduced by 5 to 6 sunshine hours in FCISD with TES device compared to without TES device.
- The quality of samples dried in ISD (without and with TES device) were found to be better compared to OSD. The colour degradation and more dust were observed in food products dried in OSD.
- The drying chamber was maintained to be higher than atmospheric temperature after the sunset and drying was completed in one day using lower input energy due to TES device in FCISD.
- The drying kinetics and energy and exergy parameters were improved in FCISD with TES device compared to FCISD and NCISD without TES device.

Future scope of work

- Further studies are required to increase the performance of ISD using different corrugations, fins on absorber plate and installing double pass or evacuated tube SAC.
- Further investigations are needed to optimize the energy and exergy parameters of FCISD and quantity of different TES materials numerically to dry the food products in a shorter period.
- Further studies are needed to use blowers powered by PV panels and maintenance of constant mass flow rate need to be investigated.
- The pre-treatment of food products and reducing the losses by proper insulation during drying are recommended for further studies.
- Further investigations to be done to get higher drying chamber temperature by tracking of sun and attaching concentrators to the SAC.

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