EXPERIMENTAL ANALYSIS ON DRYING OF AGRICULTURAL FOOD PRODUCTS IN AN INDIRECT TYPE SOLAR DRYER WITH PASSIVE AND ACTIVE MODE PROVISIONS

Submitted in partial fulfillment of the requirements
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DOCTOR OF PHILOSOPHY

In

MECHANICAL ENGINEERING

By

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IN MEMORY
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MY PARENTS

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CERTIFICATE

This is to certify that the thesis entitled "**Experimental analysis on drying of agricultural food products in an indirect type solar dryer with passive and active mode provisions"** being submitted by **Mr. Mulatu Chake Gilago (Roll No: 719132)** 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 "**Experimental analysis on drying of agricultural food products in an indirect type solar dryer with passive and active mode provisions"** 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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(Mulatu Chake Gilago)

Abstract

Renewable energy sources, more specifically, solar energy draws much focus from the global science and research communities for the fact that other energy sources are limited in nature and they are one of the major causes for environmental pollution. Additionally, high demand for energy becoming the core issue of the globe. Those issues drive the researchers for reliable and renewable energy sources. As a component of broad areas of solar energy, the solar dryer has become one of the essential applications in drying agricultural food products and other products. Drying involves simultaneous heat and moisture transport thereby improves the shelf life and quality of the product. Indirect type solar dryer (ITSD) is a category of solar dryers has a limitation of extended drying time and intermittence of solar radiation. Since long, efficient and effective techniques on solar dryers are under the investigation by the scientific and research community. More importantly ITSD seeks a holistic study related to energy, exergy, and environ-economic analysis as it is advantageous and gives a quality of energy, heat losses, environmental and economic impact. Making an optimum energy conversion for a thermal system is extremely challenging because of several parameters. But the effective way to investigate the quality, as well as quantity of energy in a system, a thorough investigation must be done on the energy and exergy parameters.

A passive set up of the ITSD having solar air collector (SAC), drying chamber with four trays and a chimney at the top (PITSD) was designed and established at NIT Warangal, Telangana state, India (17° 58′ 50.88″ N, 79° 31′ 58.08″ E). The existing setup was modified by integrating a trapezoidal duct with three inlet CPU fans powered by three solar PV panels provided at the entrance of SAC to develop an active setup (AITSD). After the test is completed in PITSD, the experiments in AITSD were followed. Similarly, the setups with thermal energy storage (TES) were established from the same PITSD and AITSD by restructuring with a rectangular framed TES system using paraffin wax. Ivy gourd, pineapple, and carrot were purchased from the Warangal local market and have been cleaned by water and cotton cloth. The mass variation and temperature data have been recorded during the experiments and analysed. Accordingly, the performance parameters such as temperature distributions, actual heat supply (Q_a), collector efficiency (η_c), drying efficiency (η_d), specific energy consumption (SEC), and specific moisture extraction rate (SMER) were investigated. The drying kinetics namely moisture content (MC), moisture ratio (MR), drying rate (DR), moisture diffusion (D_e), heat transfer (h), mass transfer (h_m) coefficients, and activation energy (E_a) were estimated. The drying

correlations between D_e, h, h_m vs. MC were developed and discussed. Exergy parameters of solar collector and drying section have been addressed. The exergy stability indicators also estimated. The environmental impact indicators such as embodied energy (E_e), energy payback period (EPBP), CO_2 emission, mitigation and credit have been evaluated. The economic analysis was performed to investigate the economic payback period (N). Finally, the overall performance parameters of the dryers have been comprehensively and comparatively analyzed based on the evaluated data.

The developed AITSD was easily been constructed from the available materials with an affordable cost to perform the active mode experiments. It enabled to perform the active drying experiments easily, suitably and appropriately for all the samples of the experiment. With nearly equivalent radiation of the drying days, the average collector outlet temperature (T_{co}) during drying all the samples was noticed to be higher in PITSD than AITSD. The Q_a was improved by 28.47, 12.1, and 11.89% during drying ivy gourd, pineapple, and carrot in AITSD compared to PITSD, respectively. Additionally, the average η_c was improved by 23.4, 12.67, and 20.94% during drying ivy gourd, pineapple and carrot in AITSD, respectively. Similarly, there were 27.45, 10.01, 27.33% increments of η_d in AITSD for the same. Similarly, The SEC and SMER were noticeably improved by using AITSD. There was 2 to 3 h reductions in drying time of the samples by using AITSD. The average DR of ivy gourd, pineapple, and carrot in PITSD and AITSD were 0.85 & 1.019, 0.375 & 0.447, and 0.502 & 0.561 kg/h, respectively. Faster DR was observed in AITSD compared to PITSD. The D_e, h, and h_m of the samples were improved in AITSD; and were increased with the decrease of MC in a logarithmic tends and were increased with time. The E_a noticed to be reduced in AITSD compared to PITSD.

Similar to the setups without TES, the T_{co} for the AITSD with TES was less than PITSD supported with TES. But there was considerable improvement on the average Q_a in the AITSD compared to PITSD. The η_c was improved by 11.9 to 16.52% in AITSD compared to PITSD with TES setups. Similarly, the η_d was enhanced by 12.59 - 27.93% for drying of the same. The D_e, h, and h_m were also considerably improved by using AITSD supported with TES; they were negatively related with MC in a logarithmic functions; but positively correlated with time. The E_a, SEC, and SMER were improved in AITSD compared to PITSD. AITSD had higher (by 15, 10.3, and 8.16% during drying ivy gourd, pineapple, and carrot, respectively) DR than PITSD. The drying time of the all samples was reduced in AITSD with TES compared to PITSD with

TES; The TES also helped the drying experiments to last more than 6 h continuously after the sunset.

During drying carrot in PITSD and AITSD without TES, the exergy inflow (EX_{in_c}), outflow (EX_{out_c}), and loss (EX_{l_c}) of the collector and drying section (EX_{in_d}, EX_{out_d}, and EX_{l_d}) were noticed to be higher for PITSD than AITSD without TES during drying carrot. Similarly, the exergy efficiency of collector (η_{EX_c}) was reduced by 40.85%; and the exergy efficiency of the drying section (η_{EX_d}) was improved by 34.87% by using AITSD. Moreover, the exergy stability indicators like waste exergy ratio (WER), improvement potential (IP), stability index (SI), and environmental impact factor (EIF) were also showed improvements in AITSD compared to PITSD. The environmental impact indicators like EPBP and CO_2 emission were higher for PITSD than AITSD while carbon mitigation and credit were better for AITSD than PITSD. The *N* was improved by 39.02% (0.4 years) in AITSD. Similarly, during drying ivy gourd in PITSD without and with TES, the EX_{in_c}, EX_{out_c}, EX_{l_c}, η_{EX_c}, and EX_{in_d} were noticed to be higher for without than with TES setup. The EX_{out_d} and EX_{l_d} were improved by 35.15 & 64.82%, respectively in with TES setup compared to without TES. And also, the η_{EX_d} was enhanced by 65.46% by applying TES in PITSD. Moreover, there were noticeable improvements in WER, IP, SI, and EIF in PITSD with TES compared to the without TES setup. Except EPBP and CO_2 emission, important environmental impact indicators were noticeably improved by applying TES in PITSD. The *N* was improved by 39.02% (0.67 years) by using TES in PITSD. Furthermore, the pineapple dried in AITSD without and with TES, the EX_{in_c}, EX_{out_c}, EX_{l_c}, η_{EX_c}, EX_{in_d}, EX_{out_d}, and EX_{l_d} were higher for without than the with TES setup. Similarly, the η_{EX_d} was improved by 64.66% in with TES setup compared to without TES. Moreover, the WER, IP, SI, and EIF were recognized to be improved in the with TES setup than without TES. All the environmental parameters except EPBP were improved. Finally, AITSD with TES showed an improvement of 34.04% (0.48 years) in *N*.

Overall, AITSD showed better improvements in all drying performance parameters, drying kinetics of the samples (ivy gourd, pineapple, and carrot), and 3E parameters. And also, PITSD and AITSD supported with TES showed better performances in 3E parameters compared to their corresponding without TES setups. Hence, in this study the AITSD showed a promising results; thus further researching is highly recommended. Uncertainty analyses were performed for the observed and estimated parameters to check the authenticity of the results.

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Nomenclature

Abbreviations

AITSD	Active indirect type solar dryer
CPU	Central processing unit
DR	Drying rate, (kg/h)
EIF	Environmental impact factor
EPBP	Energy payback period, (Year)
ITSD	Indirect type solar dryer
MC	Moisture content, (kg/kg of db or wb)
MR	Moisture ratio
PCM	Phase changing material
PITSD	Passive indirect type solar dryer
PV	Photovoltaic
SAC	Solar air collector
SEC	Specific energy consumption, (kWh/kg)
SI	Sustainability index, (%)
SMER	Specific moisture extraction rate, (kg/kWh)
TES	Thermal energy storage
WER	Waste energy ratio, (%)

Symbols

A	Air inlet area, (m^2)
C_T	Capital cost, (INR)
C_y	Yearly cost of the solar dryer, (INR)
ϱ	Density of air, (Kg/m^3)
D_e	Moisture diffusion coefficient, (m^2/s)
D_y	Number of active sunshine days, (Days)
E	Energy output of the dryer, (kWh)
E_a	Average activation energy, (kJ/mol)
EX	Exergy, (W)

F	Shape factor of a surface
h	Heat transfer coefficient, (W/m^2 K)
h_m	Mass transfer coefficient, (m/s)
h_w	Latent heat of vaporization, (kJ/kg)
I	Solar radiation intensity, (W/m^2)
IP	Improvement potential, (W)
k	Thermal conductivity of air, W/mK
L	Thickness of sample, (m)
L_d	Lifetime of the dryer, (Year)
Le	Lewis number
Lw	Latent heat of water, J/gK
$\dot{m}$	Mass flow rate, Kg/s
m	Mass of sample, (kg)
N	Economic payback period, (year)
P	Pressure, (N/m^3)
Q	Heat supplied, (W)
R	Radius of the sample, (m)
T	Temperature, (℃)
t	Total time taken to dry, (h)
v	Velocity of air, (m/s)
V	Volume, (m3)
Y	Uncertainty
cp	Specific heat of air, (kJ/kg K)

Greek symbols

μ	Chemical potential, (kJ/mol)
∞	Surrounding environment
α	Air thermal diffusivity, (m^2/s)
β	Constant
η	Efficiency, (%)

τ	Transmissivity of window glass
Subscripts	
a	Average/activation/actual/ambient
AO	Annual output
c	Collector
ch	Chemicals
d	Dryer/drying
DO	Daily output
e	Embodied
gen	Generated
in	Inlet, input, inflow
l	Loss
out	Outlet, output, outflow -
r	Solar
w	Water
y	Year

Chapter 1

Introduction

Chapter 1

1. Introduction

Nowadays, unusually, the concern of energy became the top priority of all nations more than ever since. It is because of the fastest growing rate of the world population and the mounting number of energy intensive industries. Obviously non-renewable energy sources like petroleum, coal, fossil fuel…etc. have been utilized to cope up with the multidimensional challenges related to the energy demands. And this unlimited dependence on non-renewable energy sources becomes a critical challenge for the environment. Additionally, the status of utilization of energy is an indicator of the level of advancement and civilization of a nation. As nations' civilization increases, the level of dependence on energy for daily activity will be more. These are flashpoints for the globe to look for a new trustworthy and consistent source of energy with minimum environmental risk to fulfil the bulk demand of energy. Therefore, researchers and scientists have been focusing to work restlessly to utilize renewable energy sources such as wind, solar, hydroelectric, etc. Solar drying, solar water heating, solar cooling, solar ponds, solar cooking, solar furnaces, solar distillation, and solar thermal power generation are some of the main applications of solar energy.

Moreover, these days, food insecurity, energy demand, energy supply imbalance and environmental catastrophes together with the rapid growth of the world population are becoming the most challenging assignments of the global community. Nations have been and are striving to devise an appropriate means to solve these assignments. The preservation of agricultural products and energy demand with the above factors are interrelated with one another in various ways; so dealing with one parameter is considered to be responding to the rest of them. In other terms, drying agricultural food products in solar dryers has multiple advantages; promotes food security, deals with renewable energy utilization, and contributes to environmental protection. Therefore, present work focuses on solar-thermal conversion (indirect type solar dryer) to dry agricultural food products which will be briefly discussed throughout this thesis.

1.1. Background

Solar energy has drawn much attention for its purest and abundant source. It is used for many applications because the systems can be developed at a low cost and without any harm to the environment. Post harvesting loss, contributing a lot to food insecurity is a common problem of farmers, especially in developing countries that need mechanized and technology-aided solutions with a minimum cost setups such as solar dryers [1]. Solar dryer is one of the applications of solar energy where moisture is removed from the drying object to promote shelf life by minimizing microbial decomposition [2]. Solar drying is managed by harvesting solar energy from abundant and everlasting pure sources. It is an element of broad applications of solar energy which becomes a center of attention for contemporary research and technology. Drying agricultural food products in solar dryers has multiple advantages; promotes food security, deals with renewable energy utilization, and contributes to environmental protection. In addition to environmental feasibility, solar drying would be a good area of interest for the scientific and research community striving for reliable sources of energy to satisfy high energy demand due to the rapid increment of world population and advancement of rigorously energy-dependent technologies [3]. Indirect type solar dryer (ITSD) is much advantageous than the direct type as the color change, dust formation and food wastage by animals and birds were avoided in ISD. If the air flows naturally inside the setup, then it is called passive ITSD (PITSD) and if a mechanism is introduced to promote the airflow, it is said to be active ITSD (AITSD) [4]. AITSD is preferably applicable for medicinal herbs and agricultural food products as it reduces drying and its final product is clean and standard [5]. The performance of solar dryer can be improved by applying a mechanism like using thermal energy storage to solve the intermittence of solar radiation by storing sunshine hours and discharging in off sunshine duration. Latent heat storing materials (paraffin wax) would be recommended for such application because of its thermo-physical properties. Since long, efficient and effective techniques on solar dryers are under the investigation of scientific and research community [6]. More importantly, indirect solar dryer seeks a holistic study approach related to energy, exergy, and environ-economic (4E) analysis as it is advantageous and gives a quality of energy, heat losses, environmental and economic impact [7]. Therefore, in this chapter, an introduction of solar dryer that focusses on ITSD is discussed.

1.1.1. Solar energy

The global energy demand is unprecedentedly increasing every year. Its demand is inflated by 5.8% in 2021, exceeding 2019 levels by 1.3%. Fossil fuels accounted for 82% of primary energy consumption in 2021. It was 83% in 2019. As the result of that carbon dioxide emissions from energy use, industrial processes, flaring and methane (in carbon dioxide equivalent) rose 5.7% in 2021 [8].

India is exceedingly getting successful in developing energy sectors. It is the third largest energy consuming country. Coal, oil and solid biomass constitute 80% of the energy consumption of the country. Still an expanding economy, urbanization, population growth, and industrialization result in that India faces the leading increase in energy demand of any country, across all of the energy sector scenarios to 2040. A 50% rise in India's CO_2 emissions to 2040 is the largest of any country in the world, even though India's per capita CO_2 emissions remain well below the global average. Solar power is set for explosive growth in India, matching coal's share in the Indian power generation mix within two decades [9].

Renewable energy sources, more specifically, solar energy draws much focus from the global science and research communities for the fact that other energy sources are limited in nature and they are one of the major causes for environmental pollution. Additionally, high demand for energy becoming the core issue of the globe. This is because of the rate of population growth and expansion of energy intensive technologies. These issues drive the researchers for reliable and renewable energy sources. Solar energy drawn much attention for it is purest and abundant source of energy; and it has got tremendous applications with a low cost and without any harm on environment. There are two main techniques of utilizing solar energy namely photovoltaic and solar-thermal conversion [10]. As a core application and research area of the solar energy, solar dryer (solar-thermal conversion) is discussed broadly in subsequent sections.

1.1.2. Solar drying

Solar drying (SD) is one of the ancient methods of drying where people have been removing moisture from moist objects thereby minimizing decomposition and deterioration so that shelf life could be improved and transportation can be eased. Nowadays it is getting specific attention because it is environmentally friendly and accessible to everyone at a minimum cost. As a component of broad areas of solar energy, it has become one of the essential applications in drying agricultural food products and other products. Solar drying is a mechanism that removes moisture from the object by exposing it either directly or indirectly to solar radiation. It involves simultaneous heat and moisture transport thereby improves the shelf life and quality of the product [2, 5]. In this section, different categories of solar drying such as open sun drying (OSD), direct solar dryer, ITSD, and mixed type solar dryers are discussed.

1.1.2.1. Open sun drying (OSD)

OSD (**Fig. 1.1.**) is the oldest, cheapest and traditional method of removing moisture from objects. It is a technique of exposing the drying object to sunlight in an open field (open and air solar). But its final product is poor in quality because the destruction by animals, birds, and insects. It is susceptible to spoilage due to humidity of air, non-uniform drying, high solar radiation, rain, and air pollution [4].

Fig. 1.1. Open sun drying [11, 12]

1.1.2.2. Direct type solar dryer

Another category of solar dryer is direct type solar dryer (DTSD) (**Fig. 1.2.**). In the DTSD, the drying objects are subjected to direct solar radiation through transparent glasses. Chauhan and Rathod [13] performed a comprehensive review on the studies of solar dryers and reported that solar energy is the best option to replace fossil fuel usage for drying applications. The drying time and equilibrium moisture content of potato slices were estimated experimentally by Chandramohan and Talukdar [14]. They presented that the microbial and bacterial impact of agricultural food products can be avoided by reducing the moisture content (MC) below 10%. DTSD is simple to manufacture than ITSD, and has more hygienic final product compared to open sun drying (OSD). But the products dried in DTSD may loss the quality (nutritional and medicinal content) as they are directly exposed to solar radiation.

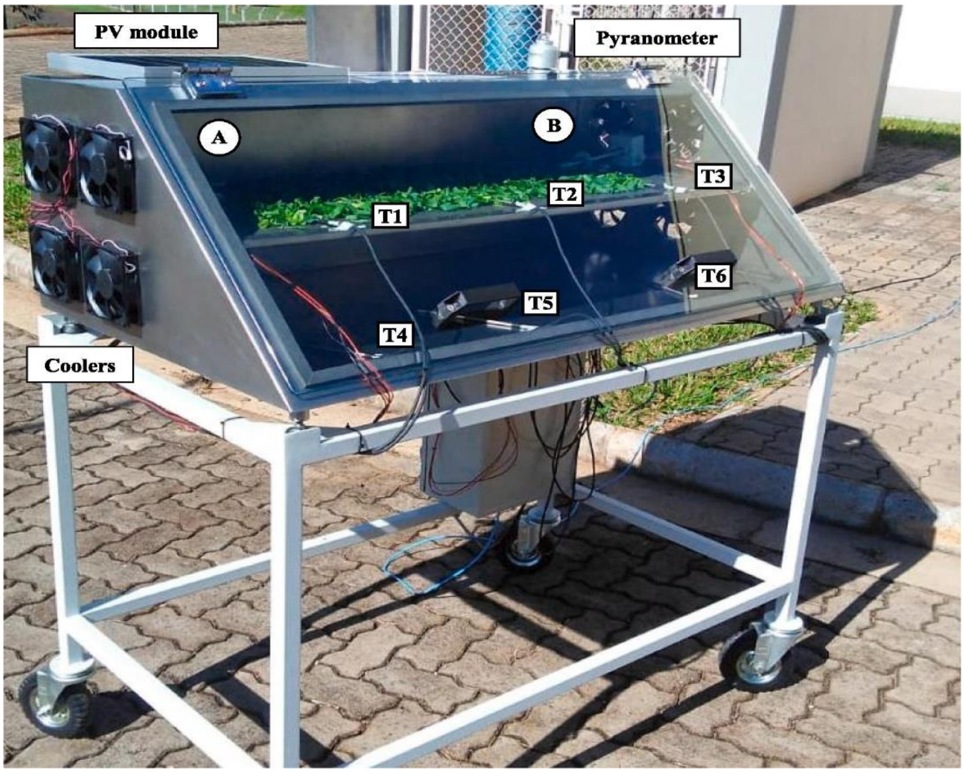


Fig. 1. 2. Direct type solar dryer [15]

1.1.2.3. Indirect type solar dryer (ITSD)

ITSD (**Fig. 1.3.**) is a kind of solar dryer where solar radiation is collected by solar air heater in the form of thermal energy. The collected thermal energy heats air that passes to drying object so that the drying takes place. Fudholi et al. [16] categorized solar drying based on the style of exposure of food products to the solar radiation as open sun drying (OSD), direct solar dryers, indirect type solar dryers (ITSD), mixed type dryers and hybrid type solar dryers. On their assessment, they concluded that solar drying of agricultural and sea products is very impressive and economical compared to other drying techniques. An ITSD is suitably preferred over a direct one to employ to dry medicinal herbs and agricultural food products which are sensitive to direct sunlight. Furthermore, AITSDs would benefit from shortening the drying time compared to PITSDs [17]. PITSD is a kind of an ITSD where the air flow occurs naturally without any external flow. But AITSD, unlike to PITSD, requires a system which pushes the air to promote the mass flow rate. AITSD is superior over passive one as it shortens the drying time and saves energy compared to PITSD.

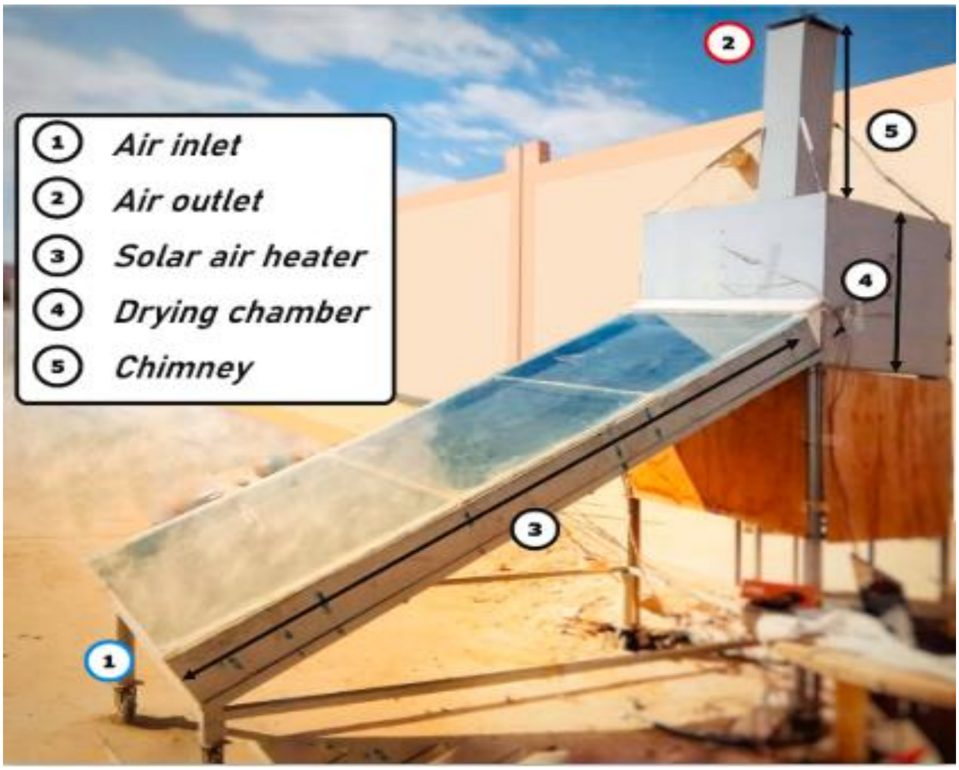


Fig. 1. 3. Indirect type solar dryer [18]

1.1.2.4. Mixed type solar dryer

The mixed type solar dryer (MTSD) (**Fig. 1.4.**) works the principle of direct as well as ITSD dryers. It consists of a SAC, a drying chamber with transparent glazing, and a chimney. In the MSD, the hot air is generated in two ways; through the SAC and through the glass which is placed on the drying cabinet. Singh et al. [19] developed an active MTSD for drying 0.5 kg of apple slices. The dryer was integrated with paraffin wax and sand as TES materials. The dryer helped to reduce apple slices' moisture content (MC) from 80 to 21.7% (wb) in 3.5 h.

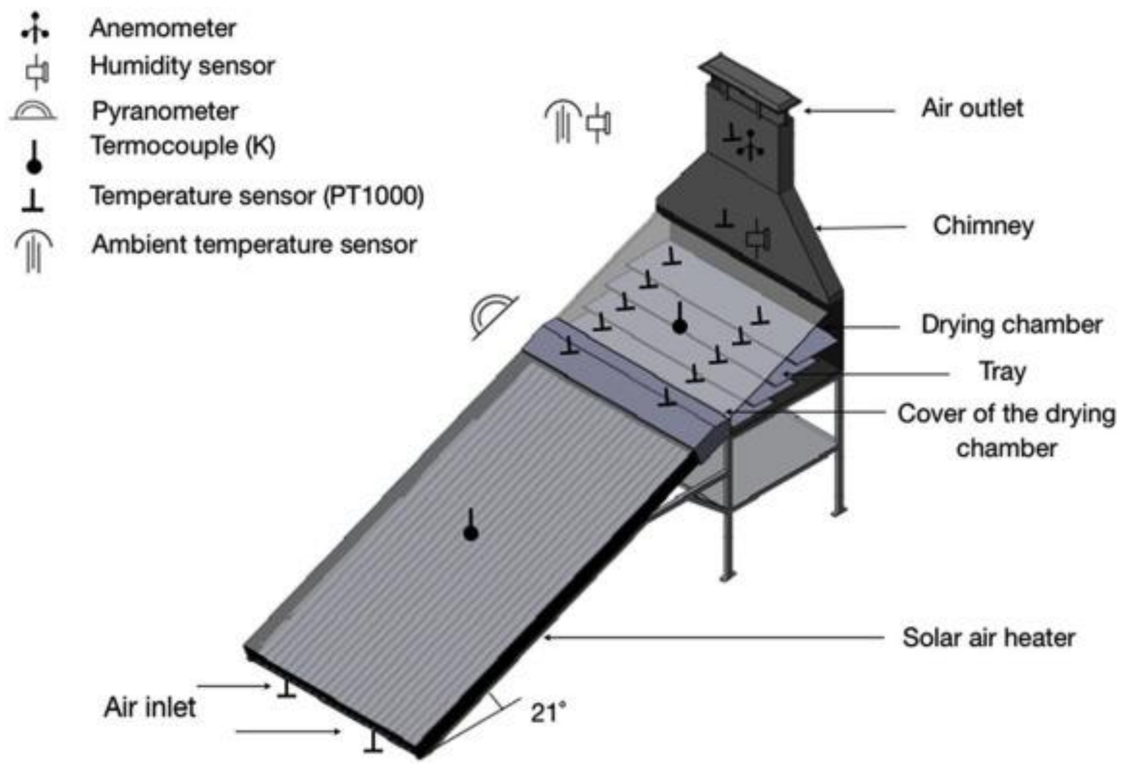


Fig. 1.4. Mixed type solar dryer [20]

1.1.3. Thermal energy storage materials

The main drawback of solar energy in applying for solar drying is its intermittence after sunset or on cloudy days. There should be a means to tackle such problems. Integrating the TES in a solar system improves the performance and minimizes the intermittence of sun energy by storing and discharging heat energy during off-sun shine hours. Energy storage system in a solar dryer is categorized as sensible heat storage system (SHS), latent heat storage system (LHS) and chemical energy storage system (CESS) [21]. The SHS is characterized by storing the energy based on the change in the temperature of a solid or liquid and specific heat. LHS generally stores energy by absorption or desorption of heat energy during phase change from solid to liquid or vice-versa. Additionally, in CESS, the energy absorption and release occurred by breaking and reforming molecular bonds. From the mentioned TES types, LHS (paraffin wax) is relatively thermally and chemically stable, resistant to corrosion, minimum sub-cooling, has high latent heat in small volume, and economical. Hence, using PCM (LHS) as TES unit came to be the choice of energy storing systems [22].

1.1.4. Exergy, environmental and economic (3E) analysis

As energy is inevitably important to human existence, its sources of generation, methods of utilization, impacts on the environment, and its economic importance are a highly concern to every nation. As of these fact, scientific society is diligently working with great care and precautions to devise techniques to make sure all energy projects are environmentally friendly, economically affordable, and efficiently utilizable as well as sustainable in nature before implementation. Proper utilization and wise use of available energy by attaining the optimum energy conversion from a suitable source with a minimum CO_2 emission to the environment is one of the core thought of energy industries and researchers [23]. Since long, efficient and effective techniques on solar dryers are under the investigation of scientific and research community. More importantly, indirect solar dryer seeks a holistic study related to energy, exergy, and environ-economic (4E) analysis as it is advantageous and gives a quality of energy, heat losses, environmental and economic impact. Making an optimum energy conversion for a thermal system is extremely challenging because of several parameters' participation. But the effective way to investigate the quality, as well as quantity of energy in a system, is through evaluation of the energy and exergy [24]. Therefore, these paramters are discused in detail in this study.

1.1.5. Overview of vegetables and fruits drying

In the next 30 years, the population of the globe is predicted to upsurge from 7.7B (2020) to 9.9B (2050) [25]. Based on that estimation, food security would be the most severe challenge of the world; more specifically developing nations. Therefore, searching for a means and getting prepared to cope up such challenges would remain an assignment for the whole nations. Minimizing the post-harvest loss of agricultural community (30 – 40% annually) is one of the areas to be dealt with [26]. Post harvesting loss, contributing a lot to food insecurity is a common problem of farmers, especially in developing countries that need mechanized and technology-aided solutions with a minimum cost like solar dryers [27].

Vegetables and fruit are very important agricultural food products for human being. They are rich in nutritional elements and high medicinal values. Simultaneously, their nature of seasonality, temperature and solar radiation sensitivity together with high moisture content needs careful handling during and after harvesting. Solar drying reduces the level of moisture content (MC) from the object so that the favorability for microbial development is decreased, and the final product can be stored long without deterioration and decaying [28]. More importantly, ITSD is preferably used to dry agricultural food products and medicinal herbs because it appropriately protects the volatile ions and radiation-sensitive nutrients. In addition to environmental feasibility, solar drying of agricultural food products might have an advantage in improving food security by minimizing harvesting losses and increasing shelf life [3].

1.1.5.1. Ivy gourd

Ivy gourd (Coccinia indica) (**Fig. 1.5 a**) is a tropical plant mainly produced in Asia (India, Thailand, etc.) which is rich in beta-carotene (major constituent of vitamin-A) and other nutrients like vitamin C, fiber, iron. Additionally, it is rich in potassium and calcium. Vacuum drying maintains beta-carotene content, but high temperature drying disturbs color and beta-carotene of the final product. But Vacuum drying is more expensive compared to solar drying [29].

1.1.5.2. Pineapple

Pineapple (Ananas comosus L.) (**Fig. 1.5 b**) is the 3rd most largely produced fruit in the world after banana and mango, with an attractive aroma and nutritional value. It takes 6 to 8 months to ripen naturally. High moisture content in it fosters high metabolism during storage which decorates it nutritional and medicinal elements. Both high temperature drying as well as wet storing seriously damage the nutritional value of pineapple; needs optimized temperature drying [30].

1.1.5.3. Carrot

Carrot (Daucus carota L.) (**Fig. 1.5 c**) is one of widely cultivated vegetables in the world. It is a rich source of vitamins, carotene and fiber content which needs maximum care and optimum temperature during drying [31]. Applying an appropriate drying method with an optimum temperature would manage the threats of vegetables and fruits during harvesting and storing. Hence, ITSD would be a kind of the drying methods which is appropriate and highly recommended for the drying of vegetable and fruits.

1.2. Motivation of the topic

Solar energy is renewable, pure and abundant in its nature; but it is not exploited yet as it is supposed to be. Even though so many of researchers and scientists have been engaged on utilizing it, the problem of efficiency remained unsolved yet. Yet another big challenge in the

3rd world countries, more specifically in Africa is food insecurity, where there is primitive farming and rain water dependency despite availability of all resources. Even those farmers who are engaged in the primitive farming produce seasonally, and would be forced to sell in cheap price during harvesting. They face hunger, starvation, and malnutrition in the other way around season. Again some of them who harvest in dry season, use OSD method which might have led them to a lot of losses due to microbial decomposition, over drying or exposure to dusts, insects and animals etc. If proper, amicable and contemplated drying methods would have been implemented, there is a possibility of minimizing food insecurity. And additionally, drying agricultural food products in solar dryers has multiple advantages: promotes food security, deals with renewable energy utilization, and contributes to environmental protection. It is this point which insighted the researchers to go through this topic.

(a) (b) (c)

Fig. 1.5. Photo snapshot of (a) ivy gourd (b) pineapple (c) carrot

1.3. Statement of the problem

Lest its inconsistency, striving to exploit the reserved potential of solar energy by any means may put a step forward to a solution of the energy related challenges. It is important to mention that solar energy - specifically solar dryers - is one of the most attractive methods of utilizing renewable energy. In line with these, ample amount of previous studies on solar drying of agriproducts are surveyed and presented in **chapter two**. From the literature review, most drying are reported in high temperature, but agriproducts are mainly sensitive to high temperature drying which needs optimum temperature and careful process that indeed can be achieved by active ITSD. Few studies are available on the estimation of drying kinetics of different agricultural food products (ivy gourd, pineapple, and carrot) in passive and active

ITSDs. The data on the performance parameters of passive and active ITSD during drying agricultural food products (ivy gourd, pineapple, and carrot) are limit. Very few studies are reported on exergy, environmental, and economic (3E) data of ITSD setup while drying agricultural products (ivy gourd, pineapple, and carrot). There is limited data on the estimation of drying kinetics of agriproducts and performance parameters of passive and active ITSD supported with TES system. Comprehensive evaluation of the performances of PITSD and AITSD in drying agricultural food products is rarely reported. Hence, the researchers targeted to contribute in narrowing the identified gaps mentioned in this section.

1.4. Aim and objectives

Aim: To develop an active mode provision to passive ITSD and to evaluate its performance during drying ivy gourd, pineapple and carrot.

Major Objectives

The work in this thesis is achieved through the followings objectives:

1. To develop an active mode indirect type solar dryer (AITSD) using three CPU fans powered by PV panels.
2. To estimate the performance parameters of passive (PITSD) and active (AITSD) during drying agriproducts (ivy gourd, pineapple and carrot).
3. To estimate the drying kinetics of agriproducts (ivy gourd, pineapple and carrot) dried in both PITSD and AITSDs.
4. To evaluate the drying kinetics of agriproducts (ivy gourd, pineapple, and carrot) and performance parameter of PITSD and AITSD with TES system.
5. To investigate the exergy, environmental, and economic (3E) parameters of the PITSD and AITSD by drying agriproducts (ivy gourd, pineapple and carrot).
6. To compare overall parameters such as performance, drying kinetics, and exergy, environmental and economic parameters of the PITSD and AITSD.

1.5. Work plan

The performance parameters of passive and active ITSDs and drying kinetics of agriproducts (ivy gourd, pineapple, and carrot), the 3E indicators have been assessed through experimental investigations. A quantum of procedures (**Fig. 1.6.**) were followed to examine the overall performance of a passive and active ITSDs without and with TES. An active mode provision was developed to promote the velocity of drying air in AITSD. Overall parameters are comprehensively analyzed and compared.

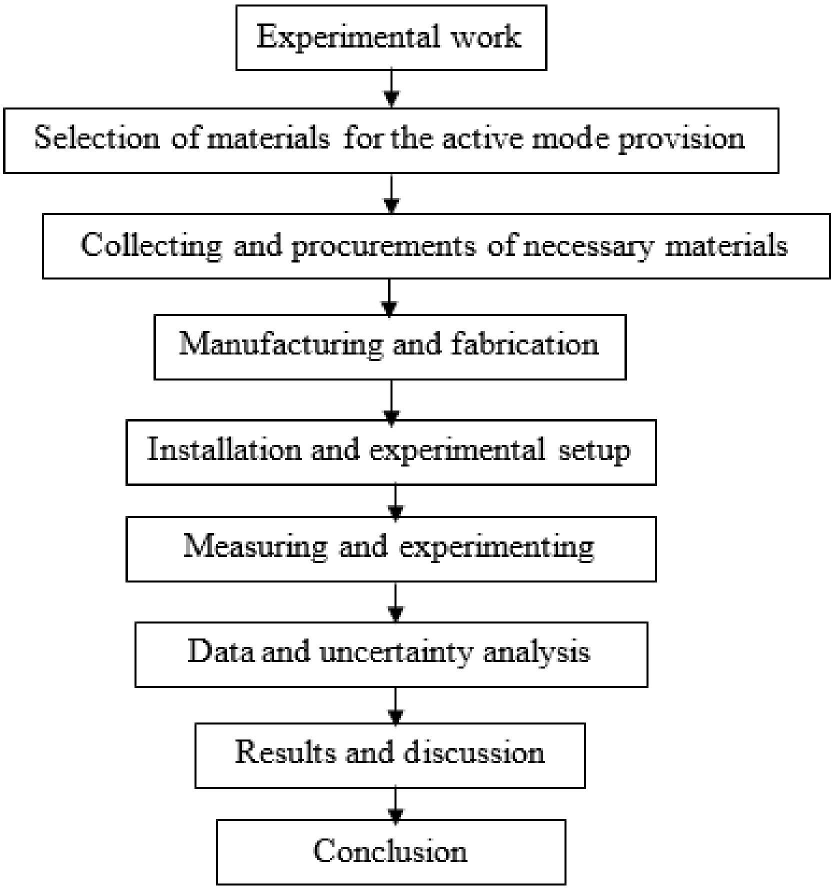


Fig. 1.6. Diagrammatic representation of work plan in flow chart

1.6. Organization of the thesis

This research work is structured in the following manner:

The **first chapter** deals with the introduction of the whole work accompanied with background and motivation. A highlight of the discrete work components such as solar energy, solar drying, TES, 4E parameters, and an overview of fruits and vegetables are introduced and discussed. Literature gaps identified from survey of the literature discussed in chapter 2 are presented here. The objectives of the current work are discussed in this part. The work plan and organization of the thesis are also included in this chapter.

The **second chapter** presents the detail review of the literature. Brief works of researchers on solar drying, solar dryers, types of solar dryers, performance parameters of ITSDs, drying kinetics of various agriproducts are presented. The merits and demerits of drying agriproducts in ITSD are discussed. Applying TES in an ITSD to dry agricultural food products is also addressed. Studies on the drying kinetics of different agricultural food products from various scholars are assessed and presented. Studies focusing on 3E parameters assessments are included in this chapter. Overall literature survey is also summarized and conclusion remarks are inferred.

The **third chapter** is related to methodology and materials used for the experimental work. Experimental setups, components of ITSD, materials employed during experiment and their precisions are presented. Experimental procedure, selection of the samples, and the initial moisture content (MC_i) of the samples are discussed. The equations employed to estimate energy and drying performance parameters, the drying kinetics, and 3E parameters are given in this chapter. The uncertainty analysis and physical properties of materials are also explained.

The **fourth chapter** discusses the results and discussion part. The performance parameters of passive (PITSD) and AITSD without and with TES are elaborated. The drying kinetics of the samples (ivy gourd, pineapple, and carrot) are described in detail. Furthermore, the exergy parameters, environmental impact indicators, and the economic importance are discussed and presented. Finally, the overall performance of PITSD (with and without TES) and AITSD (with and without TES) was comprehensively analyzed and compared.

The **fifth chapter** presents the conclusion from the experimental results. The conclusions inferred from the experimental study on the performances of ITSD during drying the samples (ivy gourd, pineapple, and carrot) are described. The future scope of the work is also included.

Chapter 2

Literature review

Chapter 2

2. Literature review

2.1. Introduction

This chapter presents the detailed survey of the literature. Brief works of researchers in different perspectives on solar drying, different solar dryers, performance parameters of ITSDs, drying kinetics of various agriproducts are presented. The merits and demerits of drying agriproducts in ITSDs are discussed. Applying TES in a ITSDs to dry agricultural food products is also addressed. Studies on the drying kinetics of different agricultural food products dried in ITSDs integrated with TES from various scholars are assessed and presented. 4E parameters and their assessments are included in this chapter. Overall literature survey is also summarized and concluding remarks are inferred. Research gaps are identified and accordingly the objectives of this thesis are framed.

2.2. Background

Solar drying is one of the ancient practices to remove moisture from objects and preserve agriproducts. It reduces the level of moisture content (MC) from the object so that the favorability for microbial development is decreased, and the final product can be stored long without deterioration and decaying [28]. Solar drying is managed by harvesting solar energy from abundant and everlasting pure sources. Solar drying is an element of broad applications of solar energy which becomes a center of attention for contemporary research and technology. Drying agricultural food products in solar dryers has multiple advantages; promotes food security, deals with renewable energy utilization, and contributes to environmental protection. Indirect type solar dryer (ITSD) is preferably used to dry agricultural products and medicinal herbs for it appropriately preserves the solar radiation-sensitive nutritional elements and volatile ions. In addition to environmental feasibility, solar drying would be a good area of interest for the scientific and research community striving for reliable sources of energy to satisfy high energy demand due to the rapid increment of world population and advancement of rigorously energy-dependent technologies [3]. Post harvesting loss, contributing a lot to food insecurity is a common problem of farmers, especially in developing countries that need mechanized and technology-aided solutions with a minimum cost like solar dryers [1]. Overall, in this chapter, studies regarding solar drying and its important tips have been comprehensively assessed and presented.

2.3. Solar energy

Except for intermittency, solar energy is one of the valuable sources of renewable energy that could be the future promise of the globe as it is providing the purest and most reliable source. It is the best option to replace fossil fuel usage for drying applications [13]. The agenda of energy saving together with utilizing from a cleaner source is supposed to be a sensitive issue of all the global community; and it should be the front line itinerary of all policy makers, researchers, scientist, industries, and organizations. That is because of a clear reason that life on earth is totally dependent on energy, which its demand is sloping up in an alarming rate as the population and energy dependent industries are growing very fast. As a matter of fact, solar energy in a variety of forms is believed to be a suitable alternative to these challenges if used properly, hence attracting the interest of researchers and other members of society [6]. Lest its inconsistency, striving to exploit the reserved potential of solar energy by any means may put a step forward to a solution of the energy related challenges. It is important to mention that solar energy - specifically solar dryers - is one of the most attractive methods of utilizing renewable energy. Due to its environmental friendly characteristics, accessibility and minimum cost, this technology is getting special attention in the present day. Using solar energy for food products drying can prevent microbial decomposition of drying products by removing moisture from them [32].

2.4. Solar dryer

Solar dryer, one of the applications of solar energy is the oldest method of preserving agricultural food products. Solar drying is a mechanism that removes moisture from the object by exposing it either directly or indirectly to solar radiation. It involves simultaneous heat and moisture transport thereby improves the shelf life and quality of the product; the microbial and bacterial impact of agricultural food products can be avoided by reducing the moisture content (MC) below 10% [14]. Taking into account how solar radiation is exposed, classified solar dryers as direct or indirect. Based on the style of applying the flow, indirect dryers are further divided into passive (natural convection) and active (forced convection) setups [2]. Comparatively, an ITSD performs better in drying medicinal herbs and agro-food products with sensitive nutrients. In their review, Lingayat et al. [4] reported that based on the way of exposure of the drying object to solar radiation, solar dryers can be controlled or uncontrolled (open sun drying, OSD). They concluded that the performance of a solar dryer was influenced by air velocity, solar intensity, humidity, volume, and texture of the drying object. Additionally, they mentioned that PITSD was advantageous over AITSD in that it was low cost and easy to manufacture, but inconvenient to control the drying rate. Udomkun et al. [33] executed a survey on the methods of preserving food grains in sub-Saharan African and Asian countries. They reported that solar drying is one of the best techniques for drying agriproducts. They reported that there are so many factors which influenced the accessibility of solar drying with pledge and must be considered during drying specific type of the drying object. Fudholi et al. [16] categorized solar drying based on the style of exposure of food products to the solar radiation as OSD, DTSD, ITSD, MTSD, and HTSD. On their assessment, they concluded that solar drying of agricultural and sea products is very impressive and economical compared to other drying techniques. Accordingly, the generalized categories of solar dryer (OSD, DTSD, MTSD, HTSD, and ITSD) with the detailed discussion of ITSD are presented in the proceeding sections.

2.4.1. Open sun drying (OSD)

OSD (**Fig. 2.1**) is the oldest, cheapest and traditional method of removing moisture from objects. It is a technique of exposing the drying object to sunlight in an open field (open and air solar). But its final product is poor in quality because of the destruction by animals, birds, and insects. It is susceptible to spoilage due to humidity of air, non-uniform drying, high solar radiation, rain, and air pollution [4]. Similarly, drying experiment was done on fenugreek leaves by Sarul et al. [34] to evaluate the drying characteristics of the sample in dryers and open sun. Various drying models have been applied to validate the test results, and statistical data were employed to compare the results. The drying characteristics of grapes were investigated by Essalhi et al. [35] by drying in PITSD and OSD. The report shows that the moisture diffusion coefficient (D_e) for the grape in PITSD and OSD was 4.08×10^{-11} and 2.34×10^{-11} m^2/s, respectively. It took 120 and 201 h in PITSD and OSD to dry the grapes from 3.74 to 0.253 (db), respectively. Mohammad et al. [36] manufactured a hybrid passive and active ITSD to experimentally investigate the performance during drying pineapple in Uganda (East Africa). Additionally, they assessed the economic importance of the system and compared with the OSD. Accordingly, they presented that the average drying air temperature was 31.9 ºC for the proposed system and 27.6 ºC for the OSD. The thermal energy was reported to be 3551 and 2952 W for the ITSD and OSD, respectively. ITSD dried the sample in 10 h while OSD took 30 h.

Fig. 2.1. Photographic view of OSD (accessed from: https://innotech-ing.com/en/tunnel_dryer.php on 05/10/2022)

2.4.2. Direct type solar dryer (DTSD)

Another category of solar dryer is DTSD (**Fig. 2.2**). In the DTSD, the drying objects are subjected to direct solar radiation through transparent glasses. Chauhan et al. [13] performed a comprehensive review on the studies of solar dryers and reported that solar energy is the best option to replace fossil fuel usage for drying applications. DTSD is simple to manufacture than ITSD, and has more hygienic final product compared to OSD. But the products dried in DTSD may loss the quality (nutritional and medicinal content) as they are directly exposed to solar radiation. Hadalgo et al. [37] made a DTSD supported by photovoltaic (PV) panels to facilitate the active mode drying experiments of the green onion by controlling moisture and calorimetric parameters. The D_e, thermal efficiency and SEC were estimated to be 5.15 $\times 10^{-9}$ and 1.15 $\times 10^{-8}$ m^2/s, 34.2 and 38.3 %, and 18.3 and 16.39 kWh/kg for passive and active mode setups, respectively. Nabnean and Nimnuan [38] dried 10 kg of banana in a direct AITD to investigate the drying performance. They designed a parabolic solar collector and a flat plate covered by polycarbonate. The researchers reported that the temperature inside the drying cabinet reached between 30 – 60ºC. It took 4 days to dry the banana from 72 to 28% (wb) while from 72 to 40% (wb) on the same days for OSD. High quality final product and reduced drying time by 40% compared to OSD with an economic payback period (N) of nearly 13 months were achieved through their study. An experimental study was executed by Mishra et al. [39] on a lab-scale PITSD and AITS greenhouse dryers to examine the thermodynamic performance, economic and environmental feasibility through 4E analysis. In their study, they found that the η_d and η_{EX_d} for the PITSD dryer were 41.5% and 4.5%, while the same for AITSD was 28.5% and 4.1%, respectively. Additionally, they reported that the carbon credit earned for passive and active setups was \$99.95 and \$91.24, and the N for the lifetime of 10 years was 2.7 and 3.2 years, respectively. An experimental study of hot air and microwave oven drying of peppermint petals by Torki-Harchegani et al. [40] showed that the samples dehydrated in the microwave at a faster rate, and in the hot air with a slower rate. Minimum D_e was found for hot air drying which was 1.809×10^{-9} m^2/s at 50ºC, and maximum D_e (110.552×10^{-9} m^2/s) was noticed for microwave setup at 800 W. Their E_a for microwave and hot air dryers was reported to be 34.05 kJ/mol and 12.46 kJ/mol, respectively. Mishra et al. [41] assessed the quantity and availability of energy, environmental and economic importance of a DTSD without load application, and they found that the exergy efficiency (η_{EX}) was 4.1 and 4.5%, respectively. Assuming that the systems have a lifetime of ten years, the payback period for the energy (EPBP) for the same was 1.5 year and 1.1 year, respectively. A drying experiment of jackfruit leather was analyzed by Chowdhury et al. [42] in order to evaluate the drying performance and drying kinetics of solar tunnel dryers. As a result, they concluded that the samples dried from a mean moisture content of 3.17 - 0.14% (db) with efficiencies of 27.45 - 42.50% and 32.34 - 65.30% respectively within two days.

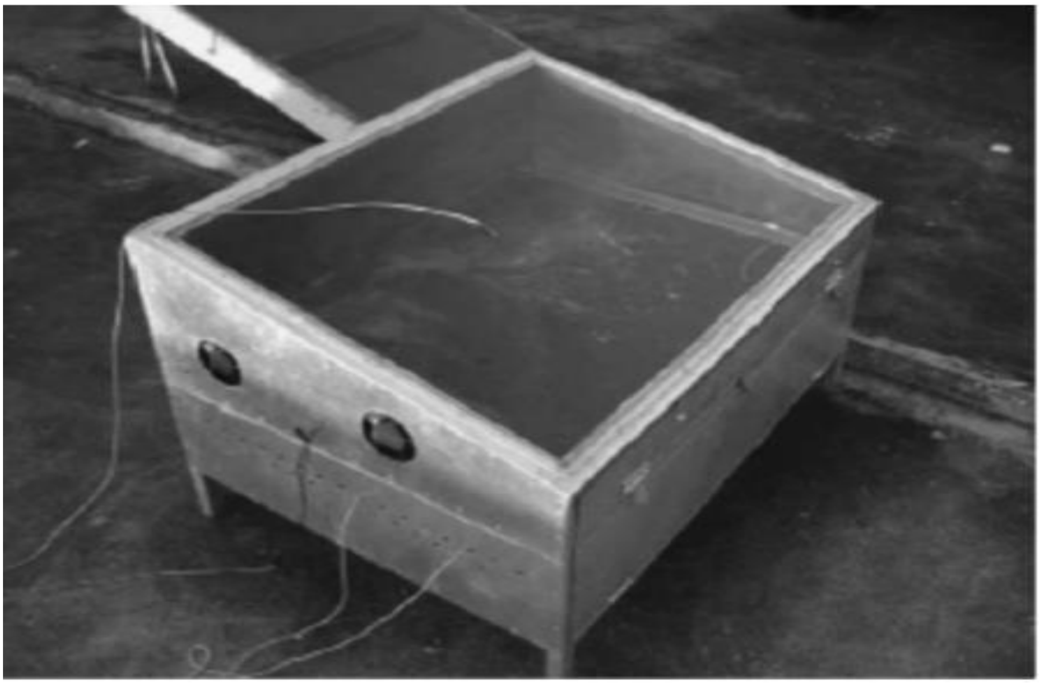


Fig. 2.2. Direct type solar dryer [43]

2.4.3. Mixed type solar dryer

The mixed type solar dryer (MTSD) (**Fig. 2.3)** works the principle of direct as well as ITSD dryers. It consists of a SAC, a drying chamber with transparent glazing, and a chimney. In the MTSD, the hot air is generated in two ways; through the SAC and through the glass which is placed on the drying cabinet. Singh et al. [19] developed an active MTSD for drying 0.5 kg of apple slices. The dryer was integrated with paraffin wax and sand as TES materials. The dryer helped to reduce apple slices' MC from 80 to 21.7% (wb) in 3.5 h. Demiray and Tulek [44] applied a MTSD (cabinet-dryer) to perform a drying experiment to examine how the drying phenomena of garlic could be influenced by temperature (55, 65, and 75 °C). They reported that the E_a and D_e were 30.582 kJ mol^{-1} and 4.214×10^{-10} to 2.221×10^{-10} m^2 s^{-1}, respectively.

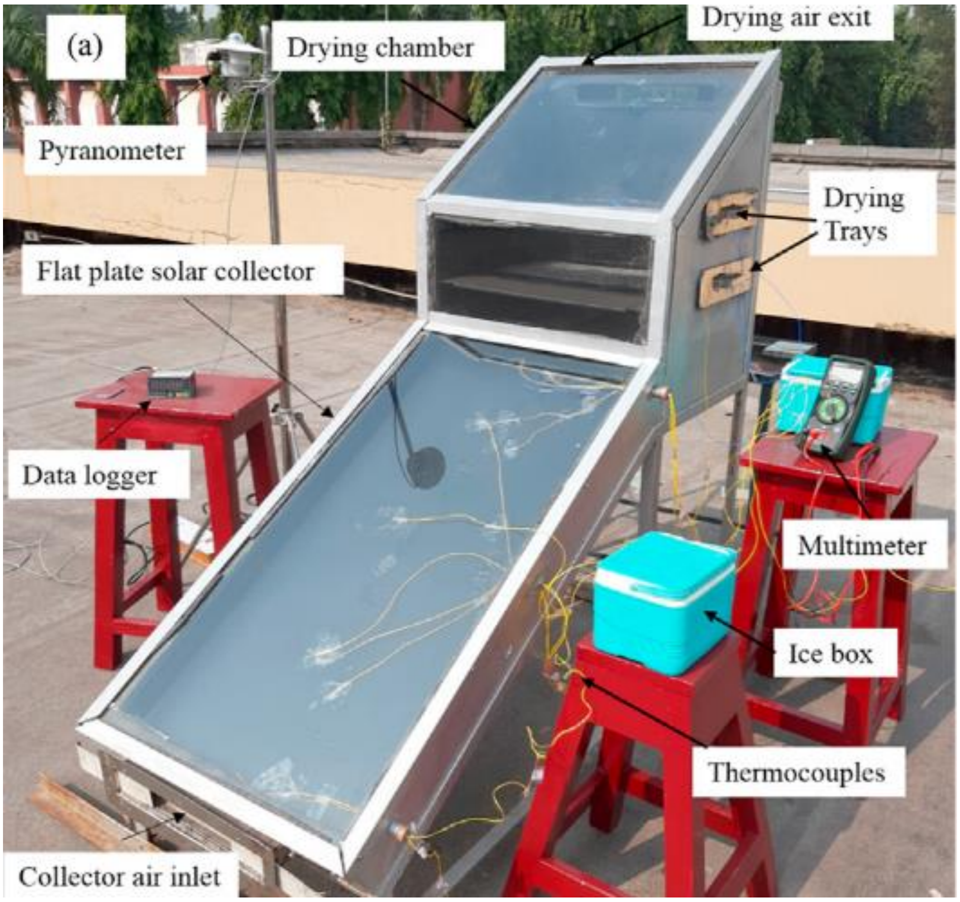


Fig. 2.3. Photo snap shot of mixed type solar dryer [45]

2.4.4. Hybrid types solar dryer (HTSD)

In a HTSD **(Fig. 2.4)**, conventional auxiliary air heating sources such as electric heater, liquid petroleum gas (LPG), biomass, coal, etc. are used along with a SAC. Moisture gets removed from the material by hot air generated from both solar and auxiliary sources of energy. This dryer provided better control over the drying compared with other dryers. Khouya [46] proposed HTSD integrated with heat pump and a concentrated photovoltaic thermal system which was able to generate electricity and heat necessary for wood drying process. About 18% reduction in drying time was observed when compared with drying operation with heat pump alone which helped to reduce the power consumption for wood drying. Ananno et al. [47] designed a geothermal-TES based HTSD (the geothermal energy from the earth's crust in the form of hot steam is integrated with TES to support dryers) in such a way that the paraffin wax is placed just below the SAC to investigate the feasibility of the system for solar drying application. They performed both numerical and experimental investigations to prove that the proposed design is valid. Accordingly, the researchers reported that the proposed system showed 20.5% improvement in efficiency. It minimized energy consumption to dry agricultural food products by 20% compared to the conventional SAC. They also recommended to use such hybrid dryers to solve the inconsistency of climates in developing countries for solar drying applications.

Fig. 2.4. Solar-wind hybrid type solar dryer [48]

2.4.5. Indirect type solar dryer (ITSD)

ITSD (**Fig. 2.5**) is a kind of solar dryer where solar radiation is collected by SAC in the form of thermal energy. The collected thermal energy heats air that passes to drying object in the drying section so that the drying takes place. In the ITSD, the food slices are don't directly exposed with solar radiation. If a strict care is taken during drying, the end products will be better hygienic, and leafy and medicinal plants' nutritional values would be preserved. Hence, ITSD is discussed broadly in this thesis work. An ample amount of necessary performance parameters and drying kinetics of various agriproducts dried in ITSD (passive and active modes without and with TES) by various scholars are broadly surveyed and presented in the subsequent sections.

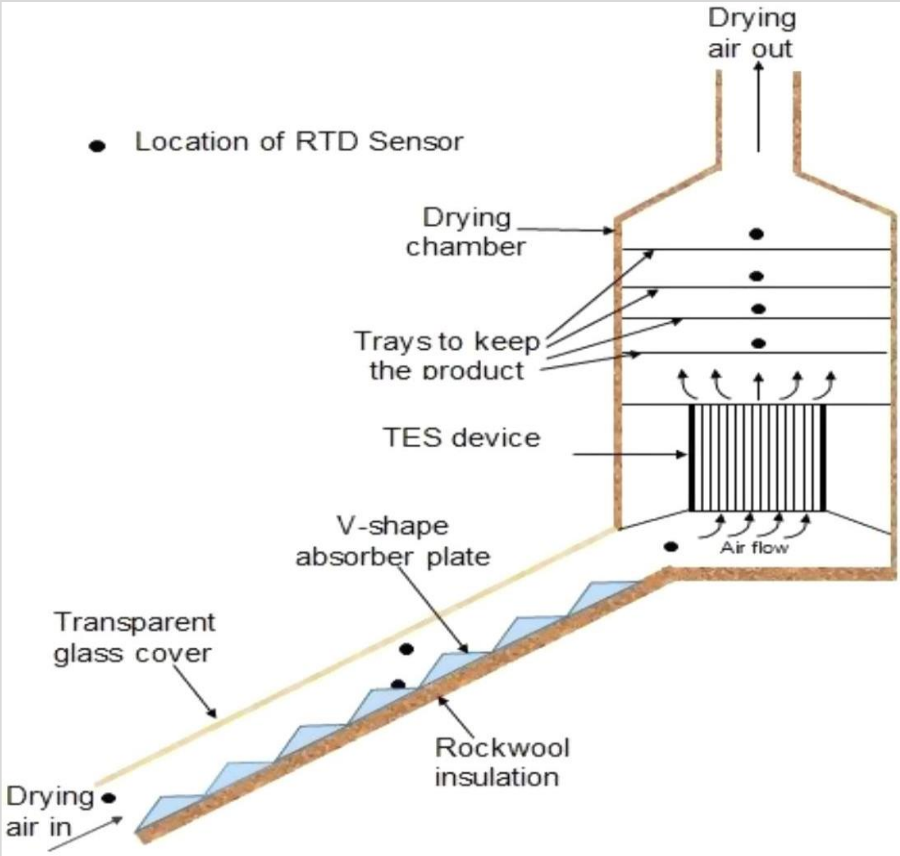


Fig. 2.5. Diagrammatic representation of ITSD [17]

2.4.5.1. ITSD without TES

An ITSD is suitably preferred over a direct one to employ to dry medicinal herbs and agricultural food products which are sensitive to direct sunlight. Furthermore, AITSDs would benefit from shortening the drying time compared to PITSDs [17]. PITSD is a kind of an ITSD where the air flow occurs naturally without any external flow. But AITSD, unlike to PITSD, requires a system which pushes the air to promote the mass flow rate. AITSD is superior over passive one as it shortens the drying time and saves energy compared to PITSD. Abuska and Akgül [49] briefly discussed the working principles, basic components and instrumentations of ITSDs in their experimental study. They examined with two setups, one with a flat plate absorber in SAC and the other with conical springs on the absorber plate. They presented that the thermal efficiency was significantly improved by the conical spring mounted absorber plate.

Sevik [50] produced an AITSD with a double-pass solar air collector to evaluate the drying performance while drying carrot slices. The moisture from the sample was reduced from 7.75 to 0.1 (db) in 220 minutes with the drying efficiency ranging from 60% to 78%. In his assessment, he recommended that strict care must be taken during drying to get quality end products. And leafy foods should better be dried in indirect solar dryers so that nutritional values would be preserved. Singh et al. [51] constructed an AITSD to perform an experimental study and investigated the impact of MC and drying duration on the energy-exergy parameters during drying banana chips. They reported that the banana samples dried from the initial MC (MC_i) of 83.8 to 11.5% (wb) with the highest drying rate of 1.1618 kg/h with a velocity of 0.8 m/s. The exergy and energy efficiencies were 24% and 58.5%, respectively. Constantino-Robles et al. [52] conducted a comparative investigation of the performances of PITSD and AITSD during drying Tithonia Diversifolia Gray (medicinal herbs). The drying performances and quality of the final dried produce were evaluated. According to their report, for both setups, the AITSD showed better quality of final product, lesser time to dry, and 71.42% higher efficiency than the PITSD. El-Sebaii and Shalaby [53] designed and constructed a AITSD to evaluate the performance of the proposed dryer by drying thymus and mint. The final MC was achieved within 34 h for thymus; in 5 h for mint in the proposed setup.

Aghbashlo et al. [54] investigated the performance of carrot drying in a semi-industrial band. The experiments were performed at various temperatures, mass flow rates and feeding rates to record mass and humidity variations. Accordingly, they reported that energy utilization was estimated between 3.78 to 25.57 kW; the energy utilization ratio in between 0.155 to 0.375; the exergy loss was evaluated in the range of 0.668 to14.16 kW. Tajudin et al. [55] performed an experimental study of drying Roselle calyx in a solar and convective heat pump dryers to analyze the influence of temperature variation and mass of the sample on the drying kinetics. Accordingly, they reported that high drying temperature and low mass of the sample fostered the faster drying of the samples. Additionally, as the temperature varied from 40 to 60 ºC, the D_e increased from 7.87×10^{-10} m^2/s to 2.05×10^{-9} m^2/s. Fudholi et al. [56] executed drying experiments of red seaweed in AITSD. They reported that the system needed a SEC of 2.62 kWh/kg to reduce the MC of the sample from 9 to 0.11 (db) in 15 h. Kasaeian et al. [57]

experimentally analysed the effect of mass flow rate on the a performance of PV-thermal system. The researchers examined the thermal efficiency of the system. Accordingly, they reported that as the mass flow rate increased, the thermal efficiency increased. The estimated thermal efficiency was in the range of 15 to 31% at mass flow rate of 0.018 (kg/s).

Mhd Safri et al. [58] surveyed the performance of different types of solar-assisted dryers and drying kinetics of various agricultural food products. Accordingly, they reported that drying agriproducts in solar-assisted dryers is more hygienic, nutritional, and healthy than other types of dryers. Erick César et al. [59] fabricated an AITSD to perform experiments on the drying characters of tomatoes and to evaluate the performance of the setup. The researchers found that the temperature of the drying section was 55 – 60ºC, η_c was 55.45%, and drying η_d was 8.8%. Asnaz and Dolcek [60] executed drying experiments of mushroom (Agaricus Bisporus) in PITSD and AITSD. They made a comparative analysis of the performances of the dyers. Accordingly, the mean values of the thermal efficiency for PITSD and AITSD were 59.74%, and 67.66%, respectively. Additionally, they identified that the most influencing factor of the drying experiment was air temperature.

2.4.5.2. ITSD with TES

The main drawback of solar energy in applying for solar drying is its intermittence after sunset or on cloudy days. There should be a means to tackle such problems. Integrating the TES in a solar system as mentioned in **Fig. 2.6** improves the performance and minimizes the intermittence of sun energy by storing and discharging heat energy during off-sun shine hours. Energy storage system in a solar dryer is categorized as sensible heat storage system (SHS), latent heat storage system (LHS), and chemical energy storage system (CESS) [21]. The SHS is characterized by storing the energy based on the change in the temperature of a solid or liquid and specific heat. LHS generally stores energy by absorption or desorption of heat energy during phase change from solid to liquid or vice-versa. Additionally, in CESS, the energy absorption and release occurred by breaking and reforming molecular bonds. From the mentioned TES types, LHS (paraffin wax) is relatively thermally and chemically stable, resistant to corrosion, minimum sub-cooling, has high latent heat in small volume, and economical. Hence, using PCM (LHS) as TES unit came to be the choice of energy storing systems [22].

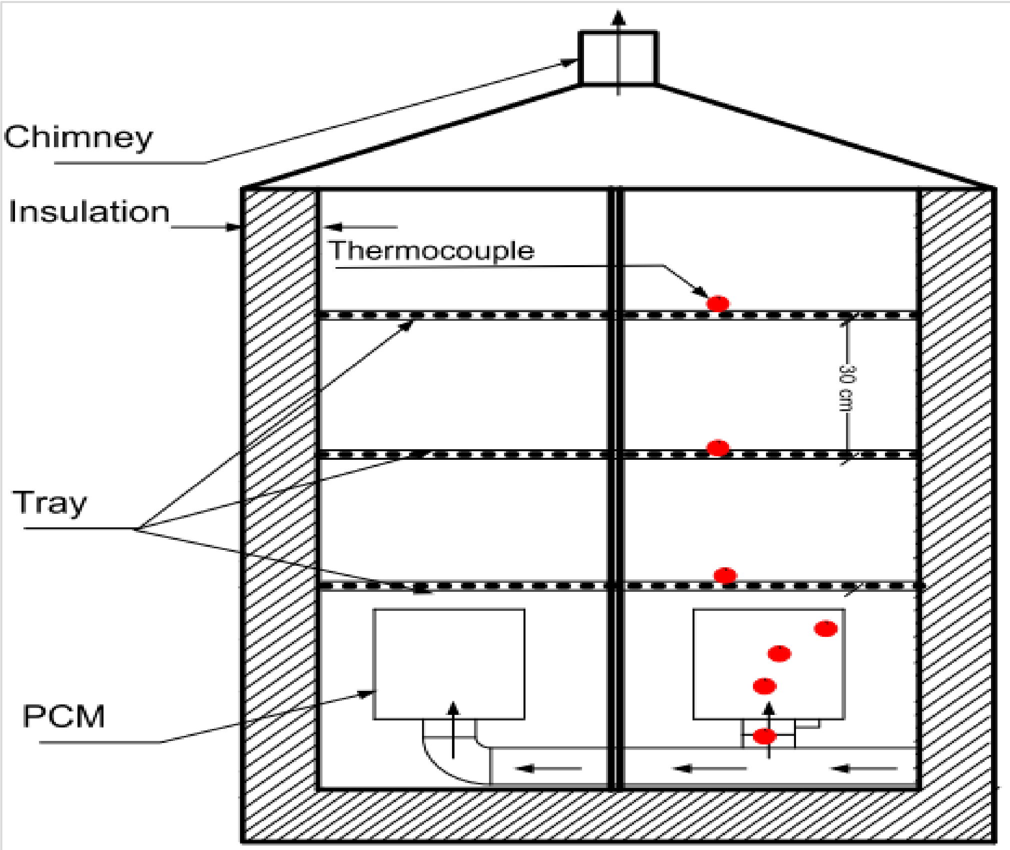


Fig. 2.6. Diagrammatic representation of drying section of solar dryer with TES [61]

Srinivasan et al. [62] performed a survey of advantages, drawbacks, types, and recent advances of solar dryers supported with TES for preserving agriproducts. They presented that the solar dryer was the best solution for food security and safety by minimizing the harvesting loss. The inability to dry the food products during the night can be overcome by integrating with a TES facility. An ITSD used to dry the products naturally is called PITSD and if the ITSD air flow is encouraged by a fan or blower, it is called AITSD. Vijayan et al. [63] conducted experiments to identify the effect of TES system and mass flow rate on the performance of AITSD while drying bitter gourd. They reported that it took 7 h to reduce the MC from 92% (wb) to 9% (wb), but it took 10 h for open sun drying. The maximum moisture extraction rate was 0.215 kg/kWh while the corresponding SEC was reported to be 4.44 kWh/ kg for the constructed setup. The drying and collector efficiencies were 19 and 22 %, respectively. Bhardwaj et al. [64] performed experiments on an ITSD integrated with a TES system to explore the performance during drying of 9 kg Valerian rhizomes. They reported that average drying rates without and with TES were 0.028 and 0.051 kg/h, respectively. The energy and exergy efficiencies of SAC for the both setups were 9.8 and 26.10%, and 0.14 and 0.81%, respectively. The overall efficiency and the SEC were 10.53% and 11.33 kWh/ kg of moisture, respectively.

Esakkimuthu et al. [22] conducted an experiment by using paraffin wax (HS-58) in a flat solar collecting plate. They assessed the feasibility of integrating PCM as TES unit with ITSD and reported an improvement of 6 drying hours with a temperature variance of 5–11 ◦C after the sundown. An experimental analysis was made by Singh et al. [65] to know the impact of integrating PCM beneath a flat SAC as a TES unit. They concluded that significant improvements were noticed in the drying parameters of TES setup compared to without TES setup. The range of temperature difference observed between the ambient and the exhaust air of SAC with TES unit was about 2 to 9 ºC, and the maximum temperature attained in the exhaust air was 48 ºC with 66% daily efficiency.

Satyapal and Chandramohan [66] numerically analyzed the influence of placing fins in a TES of AITSD. They developed two different models; one without fins and the other with fins and performed CFD simulations by applying four different air velocities. Their study showed that the two models were acceptably worked with the TES up to 10:00 PM after the sunset at the air velocity of 1 m/s, but the model with fins performed well as compared to the model without fins. And they recommended an optimized fluid velocity would better be employed in an AITSD supported TES for drying applications. Alimohammadi et al. [67] studied the impact of fluid PCMs on the performance of AITSD during the drying of apple slices. They considered four fluids such as engine oil (10W40), nano-fluid (Al_2O_3, 4%), water and glycerine for the experiment with a mass flow rate of 0.025 kg/s. They concluded that the overall thermal performance was 18.46 MJ, 17.36 MJ, 16.80 MJ and 17.76 MJ for engine oil (10W40), Nano-fluid (Al_2O_3, 4%), water and glycerine, respectively. They employed CFD to calculate the thermal characteristics of the dryer with sound accuracy. Shalaby and Bek [61] dried Ocimum Basilicum and Thevetia Neriifolia in a solar dryer with TES to investigate the drying characteristics. The highest value of drying temperature has been achieved at 0.1204 and 0.0894 kg/s for without and with TES unit, respectively. It took 18 h and 12 h for Thevetia Neriifolia and Ocimum Basilicum, respectively, to complete the drying experiment. A 4E analysis was performed on a large-scale ITSD integrated with a TES unit to investigate the practicality of the system for industrial applications and to compare it with the existing solar dryers [23]. Additionally, they assessed the exergy evaluation for the parts of the system. Accordingly, they reported that the most exergy interruption has occurred in the fans. The η_{EX_d}, CO_2 mitigation, and the EPBP of their system were 55.96%, 99.6 tonnes, and 6.82 years, respectively.

In the experiments with medicinal herbs, Bhardwaj et al. [68] evaluated the energy quality of AITSDs without and supported with TES unit (sensible and latent). According to their report, the η_c for without and with TES setups was 9.8 and 26.10%, while η_{EX_c} for the same was 0.14 and 0.81%, respectively. The total drying rate for without and with TES setups was 0.028 and 0.052 kg/h, respectively. With the SEC of 11.33 kWh/kJ, with TES achieved an overall η_d of 10.53% while the η_{EX_d} was in between 3.7 - 75.15%. El-Khadraoui [69] executed an experimental study on an AITSD integrated with a TES unit without load. They investigated the viability of using PCM in solar dryers by assessing the charging and discharging trends and by examining the quality and quantity of energy. Accordingly, they reported that the temperature of the drying section was 4 -16 °C greater than the ambient, and the humidity in the drying section was 17 - 34.5% smaller than the ambient. Additionally, the η_d and η_{EX_d} were 33.9 and 8.5%, respectively. Lakshmi et al. [70] designed a TES integrated system to perform experimental analysis on active horizontal dryers by drying black paper. The MC was reduced from 3.46 (db) to 0.14 (db) within 14 h for mixed-mode, and 23 h for AITSD dryers. The report presented the designed system showed enhancement in quality of dried product and was more beneficial from the economic aspect. A comprehensive assessment was performed by Lamidi et al. [71] on the recent status of solar dryers for drying vegetables and herbals. They confirmed that integrating TES with a solar dryer showed a good result by fostering continuous drying, and an AITSD supported with TES was found to be more trustworthy by shortening the drying time.

Aboul-Enein et al. [72] performed a parametric investigation on solar dryers without and with TES. They tried to analyze the influence of design parameters on performance. In their study, theoretical results were compared with experimental output and validated with the existing theoretical models. The final result re-assured that supporting a solar dryer with a TES promoted the drying performance and improved the quality of the dried product. To investigate the drying performances of potato slices with an active wind-powered solar dryer, Ndukwu et al. [73] used glycerol as a TES. As reported, the SEC range was 2.85-3.7 kWh/kg, the drying efficiency ranged from 25 to 31.4%, and the overall energy consumption ranged from 4.1 to 4.98 MJ. A range of 14.5 to 80.9% was recorded for energy efficiency. Atalay et al. [74] built a solar dryer with a packed bed TES unit and executed experiments to investigate the drying rate of apples. They also integrated a waste heat recovery system by which 50-60% of waste heat was estimated to be recovered to maintain the air temperature at 50-60 ºC. They reported that the energy stored in the packed bed sufficiently dried the sample slices. Kabeel et al. [75] conducted an experimental study to explore the performance of an active solar dryer supported with TES (39 kg paraffin wax). The influence of mass flow on the efficiency of the dryer has been assessed. According to the authors, the system maintained a variation of 8.6 °C between ambient and outlet temperature for 4 h after the sunset. And 10.8 – 13.6% improvement in efficiency was noticed in the dryer with the TES system. Ho et al. [76] analyzed the thermal storage ability of micro-capsulated PCM. They reported that the use of PCM increased the rate of thermal storage and minimized heat loss.

2.5. Exergy, environmental, and economic (3E) analysis

As energy is inevitably important to human existence, its sources of generation, methods of utilization, impacts on the environment, and its economic importance are a highly concern to every nation. As of these fact, scientific society is diligently working with great care and precautions to devise techniques to make sure all energy projects are environmentally friendly, economically affordable, and efficiently utilizable as well as sustainable in nature before implementation. Proper utilization and wise use of available energy by attaining the optimum energy conversion from a suitable source with a minimum CO_2 emission to the environment is one of the core thought of energy industries and researchers [23]. Since long, efficient and effective techniques on solar dryers are under the investigation of scientific and research community. More importantly, indirect solar dryer seeks a holistic study related to energy, exergy, and environ-economic (4E) analysis as it is advantageous and gives a quality of energy, heat losses, environmental and economic impact. Making an optimum energy conversion for a thermal system is extremely challenging because of several parameters' participation. But the effective way to investigate the quality, as well as quantity of energy in a system, is through evaluation of the energy and exergy [24]. Therefore, these paramters are discused in detail in this study.

Ramadan et al. [27] studied the economic and environmental merits, demerits and pitfalls of solar dryers. They addressed the working principles, parts and categories of ITSD on their report and summarized that use of a solar dryer (during drying 120 kg of carrot) reduced 6400 kg/month CO_2 emissions, saved 780$/month as compared to conventional sources of energy such as fossil fuels, and its payback period was found to be 10 months. Reddy et al. [77] performed a comparative analysis on natural and AITSD based on exergy, energy and economical paybacks by drying green chilli. They presented that the collector performances were 63.3 and 53.84%, and the drying efficiencies were 10.4 and 8.9% for PITSD and AITSD, respectively. Mugi and Chandramohan [78] performed an energy and exergy evaluation to evaluate the characteristics of active and passive solar dryers. They reported that the mean drying and collector efficiencies to be 24.95 and 74.98%, and 20.13 and 61.49%, respectively for active and passive arrangements. Exergy loss of the drying section was 0.062 to 21.99 W, and 0.394 to 24.99 W for the same, respectively.

Amjad et al. [79] performed an experimental study to examine the quality and quantity of available energy during drying green chili in a solar collector coupled with a gas burner at 60 °C. They applied three different heat sources for the drying test and suggested that a comprehensive audit of energy was required. Tiwari and Tiwari [80] numerically investigated the effect of the collector size and velocity of the fluid on the thermal energy efficiency and the exergy efficiency of the system. They reported that as the size of the SAC increased in 5 folds, the thermal and exergy efficiencies were decreased from 61.56% to 42.22% and 28.96% to 19.11%, respectively. Ndukwu et al. [81] examined the performance of a passive ITSD supported with $Na_2SO_4.10H_2O$ and NaCl as a sensible heat storage unit. Sustainability indicator, index and waste-exergy ratio have been evaluated and mentioned that nearly 602 tonnes of CO_2 could be avoided per annum if solar dryers were effectively used. An environ-economic analysis of a greenhouse solar dryer provisioned with various PV technologies has been performed by Saini et al. [82]. The earn of carbon credit, embodied energy, CO_2 mitigation and energy payback were evaluated for the respective setups. A statement in the report states that the estimated parameters could be used to determine the system's reliability and sustainability.

The influence of the position of trays in an active hot air dryer during drying of banana and bitter gourd has been performed by Arun et al. [83]. Setting the rate of mass flow between 0.015 to 0.03 kg/s, banana dried in 10 h whereas, bitter gourd took 18 h to dry uniformly throughout the trays. Exergy loss was evaluated to be decreasing with the rise of mass flow rate. The rate of energy utilization has resulted in 45.3% - 47.9%. In the experiments of drying bitter gourd in a greenhouse dryer developed by Ahmed et al. [84], they analyzed the 4E of the hybrid drying approach. Compared to OSD, which took 15 h to dry the sample products from 88.14 to 11.01% (wb), their proposed setup reduced the drying time to 8 h. The economic payback period for this process was 0.4907 years, and the setup cost was 22664.30 INR

($294.50). For 35 years, the system can earn carbon credits of 16844.76 to 67379.05 INR ($218.89 to $875.57) for mitigating 46.28 tonnes of CO_2.

Chauhan et al. [85] developed passive and active greenhouse dryers for bitter gourd flakes. The researchers investigated the drying kinetics, the energy, and environmental impacts of the system, thereby comparing the thermal modeling and the drying kinetics. Accordingly, they reported that the EPBP for active and passive mode dryers was 2.35 and 1.68 years, and the net CO_2 mitigation for the same was 33.04 and 36.34 tonnes, respectively. As part of their study on the drying properties of solar tunnel dryers and drying characteristics of Jackfruit leather, Chowdhury et al. [42] performed an experimental analysis. Their results indicated that the samples dried from 76 to 11.88% (wb) within 2 days, with η_c and η_d in the range of 27.45 - 42.50%, and 32.34 - 65.30%, respectively. The η_{EX_d} ranged from 32 to 69%, with a mean value of 42.47%. Singh et al. [51] constructed an AITSD to perform the experimental study and investigate the influence of MC and drying duration on the energy-exergy parameters during drying banana chips. They reported that the banana samples dried from 83.8 to 11.5% (wb) with the highest drying rate of 1.1618 kg/h and 0.8 m/s. The η_{EX_d} and η_d were 24% and 58.5%, respectively.

It has been shown both numerically and experimentally by Kottayat et al. [86] that the shape of the fins affects SAC performance. As a result of their analysis, a dryer with a triangular rib configuration showed better energy-saving performance than rectangular rib configuration and a smooth rib configuration by drying okra and bananas. Using solar collector integrated by a gas burner of 60°C, Amjad et al. [79] conducted an experiment to assess the energy and exergy during drying green chilli. During the drying test, they used three different heating sources and recommended an energy audit with a multi-criteria approach would give a better accuracy on the estimation of availability and quantity of energy. A comprehensive survey of solar dryer with a flat plate SAC focusing on the energy and exergy performances was executed by Fudholi and Sopian [87]. The researchers comparatively assessed the experimental and theoretical results. Accordingly, they reported that the $\eta_{EX\text{-}c}$ and energy efficiency (η_c) of the collector during indoor application were in 8 to 61% and 30 to 79%; for outdoor applications 30 to 57% and 28 to 62%, respectively. Gupta et al. [88] constructed a solar dryer with a photovoltaic nature to investigate the sustainability indicators of the system based on 4E analysis during drying star fruit. Accordingly, they reported that the sample dried in PITSD and AITSD from

10.11 to 0.91 (db) in 14.5 and 12.5 h, respectively. The energy efficiency for the systems was 43.58 and 69.27%; and the $\eta_{EX\text{-}d}$ for the same 17.89 and 31.12% for PITSD and AITSD, respectively. Similarly, η_d was 13.98 and 15.27%, respectively.

Shoeibi et al. [89] performed a numerical investigation of the effect of V-shape fins on the performance of SAC in terms of electrical and thermal efficiency together with the economic and environmental assessments. Accordingly, the CO_2 mitigation, electrical and thermal efficiencies was found to be highest for the collector with highest number (24) of fins considered in the study. The electrical and thermal efficiencies were enhanced by 8.7% and 30.6%, respectively compared to the collector without any fin. Over the course of its lifetime (25 years), the system has mitigated 44.19 tons of CO_2. An experimental and theoretical study was conducted by Lingayat et al. [90] to investigate the performance of PITSD during the drying of bananas. According to the results of their study, the exergy losses and efficiency of the PITSD were reported to vary between 3.26 and 25.2, and 7.38 and 45.3%, respectively.

2.6. Overview of vegetables and fruits drying

In the next 30 years, the population of the globe is predicted to upsurge from 7.7B (2020) to 9.9B (2050) [25]. Based on that estimation, food security would be the most severe challenge of the world; more specifically developing nations. Therefore, searching for a means and getting prepared to cope up such challenges would remain an assignment for the whole nations. Minimizing the post-harvest loss of agricultural community (30 – 40% annually) is one of the areas to be dealt with [26]. Post harvesting loss, contributing a lot to food insecurity is a common problem of farmers, especially in developing countries that need mechanized and technology-aided solutions with a minimum cost like solar dryers [27].

Vegetables and fruit are very important agricultural food products for human being. They are rich in nutritional elements and high medicinal values. Simultaneously, their nature of seasonality, temperature and solar radiation sensitivity together with high moisture content needs careful handling during and after harvesting. Solar drying reduces the level of MC from the object so that the favorability for microbial development is decreased, and the final product can be stored long without deterioration and decaying [28]. More importantly, ITSD is preferably used to dry agricultural food products and medicinal herbs for it appropriately preserves the solar radiation-sensitive nutritional elements and volatile ions. In addition to environmental feasibility, solar drying of agricultural food products might have an advantage in improving food security by minimizing harvesting losses and increasing shelf life [3]. Ong [91] theoretically analyzed by formulating a drying model for tropical fruits and validated the same with experimental drying kinetics of banana slices, thereby confirmed that the model was capable of estimating drying kinetics. Therefore, the three products (ivy gourd, pineapple, and carrot) selected for this experimental analysis of this thesis work. And various agriproducts dried by different researchers are summarized in the following sections.

2.6.1. Vegetables

2.6.1.1. Carrot

Carrot (Daucus carota L.) is one of widely cultivated vegetables in the world. It is a rich source of vitamins, carotene and fiber content which needs maximum care and optimum temperature during drying [31]. Applying an appropriate drying method with an optimum temperature would manage the threats of vegetables and fruits during harvesting and storing. Hence, ITSD would be a kind of the drying methods which is appropriate and highly recommended for the drying of vegetable and fruits. Sevik [50] reported that the solar dryers were predominantly utilized for drying leafy foods and the eventual outcome would be perfect and sterile, if all the important cares and precautions were made during drying. They designed and manufactured a double-pass SAC supported by heat pump and photovoltaic unit for drying carrot. It took 220 minutes to dry the carrot from 7.76 to 0.1 g/g of db, and the thermal efficiency was estimated to be 60% to 78%.

2.6.2. Fruits

2.6.2.1. Ivy gourd

Ivy gourd (Coccinia indica) is a tropical plant mainly produced in Asia (India, Thailand, etc.) which is rich in beta-carotene (major constituent of vitamin-A) and other nutrients like vitamin C, fiber, iron. Additionally, it is rich in potassium and calcium. Vacuum drying maintains beta-carotene content, but high temperature drying disturbed color and beta-carotene of the final product. But Vacuum drying is expensive compared to other types of drying [29]. Kulkarni and Vijayanand [92] presented that ivy gourd (Coccinia Indica L.) produced in India was categorized under the Cucurbitaceae family, which is a well-known tropical vegetable with important nutritional qualities such as hypoglycaemic effect and contains an ample amount of ascorbic acid. Its local name is ‘Dondakaya’ in Warangal, India. They executed an experimental study to investigate the quality characteristics of an ivy gourd which was pretreated by potassium meta-bisulfate and dehydrated 4.6% MC at 50 ±1°C. They claimed that the dehydrated and packed foods in low density polyethylene covers preserved for 4-6 months with highly acceptable quality.

2.6.2.2. Pineapple

Pineapple (Ananas comosus L.) is the 3rd most largely produced fruit in the world after banana and mango, with an attractive aroma and nutritional value. It takes 6 to 8 months to ripen naturally. High moisture content in it fosters high metabolism during storage which decorates it nutritional and medicinal elements. Both high temperature drying as well as wet storing seriously damage the nutritional value of pineapple; needs optimized temperature drying [30].

Additionally, solar drying of green peas [1], carob seeds (Ceratonia siliqua L.) [32], grapes [35], peppermint leaves [40], jackfruit leather [42], carrot [48, 51], Tithonia Diversifolia Gray (medicinal herbs) [52], jackfruit leather [42], tomatoes [59], mushrooms [60], thymus and mint black pepper [70], green chilli [77], banana [36, 80], mushroom [93], green chilli [94], chilli [95], apple and watermelon [96], and Citrus Aurantium [97], terfezia boudieri truffle [98], banana [87, 96], apple and water melon slices [100], potato [101], sweet cherry [102], black ginger [103], ivy gourd and turkey berry [104], green chilli (capsicum annum) and okra (abelmoschus esculentus) [105], pears slices [106], fenugreek leaves and turmeric [107], coffee beans [108], ivy gourd and turkey berry [104], grapes [109], red chilli [110], and potato [111] were dried in various types of solar dryers and plainly showed a promising future of ITSD.

2.7. Conclusive remarks from the literature

From the survey of the literature, the following concluding remarks are summarized:

- Post harvesting loss was the most prominent problem of all the primitive farming community, needing helping hand from different perspective to solve their problem.
- Solar dryers are well known for drying agricultural food products and other products such as medicinal herbs with a sensitive nature of the nutrients, would possibly denatured if exposed to direct sunlight. And hence, some studies recommended that agricultural food products and medicinal plants would better be dried in ITSD dryers to preserve the nutritional nature than drying on direct dryers.
- All the studies proved that ITSD was an effective dryer compared to other dryers as it produced more hygienic and quality final products compared to other types of dryers.

- The performance of the ITSD can be improved using various mechanisms like supporting with TES materials, improving mass flow rate of the drying air, by enhancing the efficiency of SAC.
- And again, improved drying time, enhanced drying performance and quality of the dried objects were advantages of ITSD supported with TES.
- Mass flow rate, temperature, relative humidity, the intensity of solar radiation, and volume and texture of the drying objects were the determining factors of drying performance, but the drying air temperature was the most influencing to control the process.
- There is shortage of the data on the performance parameters, drying kinetics, and 3E analysis of PITSD and AITSD (without and with TES) during drying ivy gourd, pineapple, and carrot. It indeed needs a comprehensive study of all the parameters.

2.8. Literature gaps

Among the literature, few studies on solar drying dealt with PITSD [2, 7, 34, 50, 90, 96, 112] and few others dealt with AITSD [63, 78, 88, 93, 110, 113, 114]. But no study is reported on comparative analysis of passive and active ITSDs during drying ivy gourd, pineapple, and carrot. There are some studies on estimating the drying kinetics such as drying rate [37, 115, [116], actual heat supplied (Q_a) [77], D_e [37, 115–117] and heat and mass transfer coefficients (h and h_m) [118, 119] during solar drying of food products. Still there is no study used the results of drying parameter for comparison of passive and active ITSDs during the solar drying process of the samples. Very few studies estimated and analyzed the performance parameters such as η_d [49, 63, 64], η_c [49, 63], E_a [63, 64, 118, 119], SEC [37, 49, 63, 120] and specific moisture extraction rate (SMER) [37, 94, 96, 120]. But no comparative data of these output parameters of passive and active ITSDs are reported. There is no data on drying correlation for D_e, h and h_m vs. MC during drying of ivy gourd, pineapple, and carrot in both passive and active setups.

And again, some studies contributed to identify the significance of TES system namely: for solar water desalinations [121], for SAC [122, 123], for LHS [124], for the thermal conductivity (charging and discharging) of LHS [125–127], for drying agricultural food products [67, 128, 129], and to assess the viability of PCM for the solar thermal applications [73, 130, 131]. Data on the drying kinetics of agriproducts especially of ivy gourd, pineapple, and carrot dried in PITSD and AITSD supported with TES are limited. Moreover, some studies discussed on the thermal applications of solar dryer [73, 123, 125, 131], few on TES system [67, 132], few studies on drying herbal products [122, 128], very few analyzed the thermal conductivity of PCM [127, 133]. But no study is reported on the performance evaluation (performance parameters and drying kinetics) of PITSD and AITSD integrated with TES during drying ivy gourd, pineapple, and carrot. Additionally, there is no reported on drying correlation of D_e, h and h_m vs. MC of drying of ivy gourd, pineapple, and carrot in passive and active ITSD supported with TES.

Furthermore, based on the current literature surveys, a number of studies have been carried out on different types of solar dryers and their applications, both theoretically and experimentally, for drying various agriproducts, including: medicinal herbs. Most of the studies were performed on PITSD [2, 7, 34, 90], 112, AITSD [78, 88, 93, 110, 113], ITSD without TES [51, 79, 86, 134, 135] and with TES [3, 7, 68, 128, 136]. It, however lacks data on the performance of the two setups based on the comparative analyis of 3E indicators during drying ivy gourd, pieapple, and carrots. Few of the studies dealt with the availablity and quanity of energy [42, 79, 90]. On the other hand, there is no information on the energy and exergy evaluation parameters in a PITSD (without and with TES) and an AITSD (without and with TES) for drying ivy gourd, pineapple, and carrot slices. Very few studies on exergy sustainablity indicators such as environmental impact factor (EIF), the improvement potential (IP), waste energy ratio (WER), and the sustainability index (SI) were reported [39, 42, 61, 137–139]. But no sufficient data on exergy sustainable indicators in a comprhensive manner. There have also been studies that assess the impact of solar drying on the environment and the economy [23, 27, 39, 84, 85, 94, 140–142]; however, there are no data found on the environmental impacts and economics of drying ivy gourd, pieapple, and carrots dried in a passive and active setups (without and with TES). More importantly, no study found on the comprehensive analyis on the performance paramters of passive and active (without and with TES).

2.9. Specific Objectives

Based on the figured out literature gaps and highlights of literature, the following specific objectives under the major objectives (**mentioned in Chapter-1, page 12**) are framed to fulfill the gaps of the existing literature:

Under major objective 1.

- To select required materials for the active provisions in ITSD.
- To manufacture a trapezoidal duct suitable for integration with CPU fans.
- To integrate all the parts with the existing PITSD and make ready for AITSD and conduct drying experiments of ivy gourd, pineapple, and carrot.

Under major objective 2

- To perform drying experiments, record data and evaluate the temperature distribution in PITSD and AITSD during drying the sample.
- To estimate the Qa for both passive and active modes.
- To calculate the η_c and η_d of both setups.
- To estimate the SEC and SMER for both setups.
- To make a comparative analysis of both setups based on the evaluated performance parameters.

Under major objective 3

- To evaluate the *DR* of the samples dried in PITSD and AITSD.
- To estimate the D_e, h, and h_m for PITSD and AITSD during drying the samples.
- To calculate the E_a for both passive and active setups.
- To develop a correlation between D_e, h, and h_m vs. MC of the two setups.
- To analysis both setups comparatively based on the results of drying kinetics.

Under major objective 4

- To perform drying experiments on passive and active modes ITSDs supported with TES, and analyze the data.
- To estimate the drying kinetics such as E_a, *DR*, h_m, h, and D_e of the samples dried in PITSD and AITSD supported with TES.
- To calculate the performance parameters namely Q_a, η_c, η_d, SEC, and SMER of both passive and active setups provisioned with TES.
- To make a comparative analysis of both without and with TES setups during drying the samples.
- To develop drying correlations between the variables (h, D_e, and h_m) viz. MC for both setups supported with TES.

Under major objective 5

- To estimate exergy parameters (exergy inflow, outflow, loss, efficiency) for the SAC of passive and active setups (without and with TES).
- To calculate the exergy parameters (exergy inflow, outflow, loss, efficiency) for the drying section of passive and active setups (without and with TES).
- To evaluate the exergy stability indicators (WER, IP, SI, and EIF) of PITSD and AITSD (without and with TES).
- To evaluate the economic impact indicators (capital cost, annual cost, savings, and N) of PITSD and AITSD (without and with TED).
- To examine the environmental impact parameters (E_e, carbon emission, mitigation, carbon credit, EPBPR) for both setups (without and with TES).
- To compare passive and active setups based on the results of the evaluated parameters.

Under major objective 6

- To assess overall drying performance parameters comparatively for passive and active ITSD modes.
- To analyse overall drying kinetics of passive and active modes comparatively.
- To evaluate overall 3E parameters comparatively for passive and active ITSD modes.

To make a comprehensive assessment and recommend a better setup based on overall evaluations of all parameters of passive and active modes.

Chapter 3

Materials and methods

Chapter 3

3. Materials and methods

3.1. Introduction

This chapter is related to methodology and materials used for the experimental work. The working principle of indirect type solar dryer (ITSD), experimental setups, components of ITSD, materials employed during experiments and their precisions are presented. Experimental procedure, selection of the samples, and the MC_i of the samples are estimated and mentioned. Additionally, the equations employed to estimate energy and drying performance parameters, the drying kinetics, and 3E parameters are discussed in this chapter. Moreover, the uncertainty analysis and physical properties of materials used are also explained.

3.2. The working principle of ITSD

The basic principle of ITSD is that solar radiation (energy) is collected by a SAC. The air heated by the SAC is allowed to pass though the drying object where simultaneous convective heat and mass transfer would take place. The components and working principles ITSD are diagrammatically represented in **Fig. 3.1.**

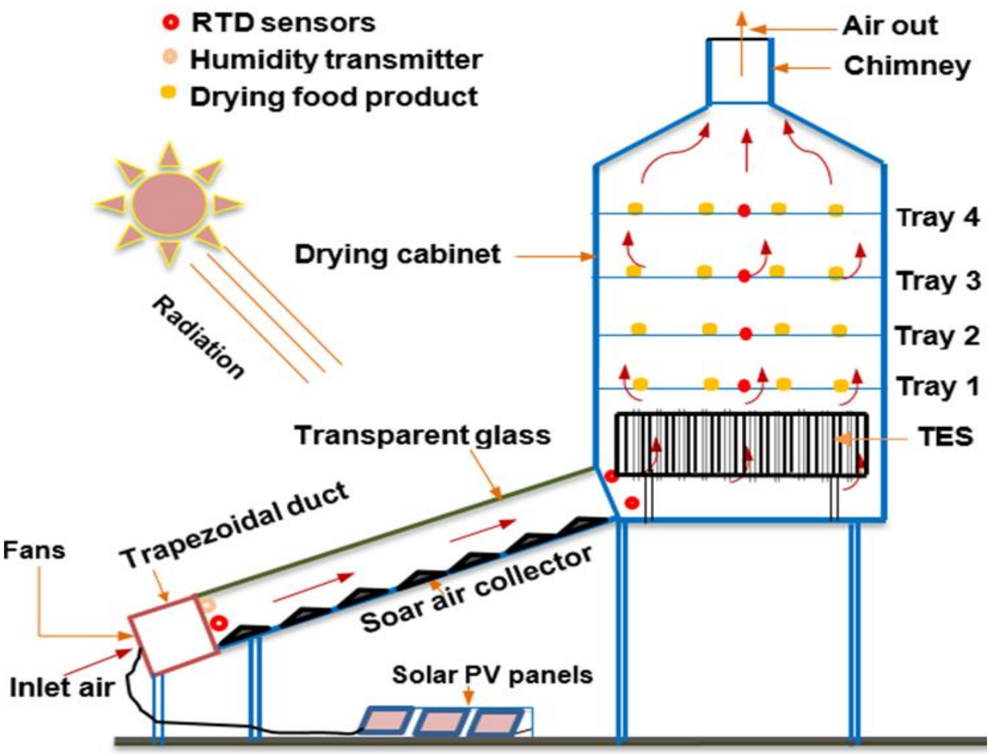


Fig. 3.1. Diagrammatic representation of working principle of ITSD

3.3. The experimental setup

The generic experimental set up of the ITSD (**Fig. 2.2 a**) was designed and established at NIT Warangal, Telangana state, India (17° 58′ 50.88″ N, 79° 31′ 58.08″ E), which has been utilized to dry variety of agricultural products. The experimental setup contains a solar air collector (SAC), drying chamber with four trays and a chimney at the top. The basic components and their precision are presented in **Table 3.1**. The experimental setup used for passive setup has been modified by integrating a trapezoidal duct with three inlet CPU fans provided at the entrance of SAC to develop an active setup as shown in **Fig. 2.2 (b)**. The CPU fans were run using solar PV panels. Therefore, there was no artificial energy used in both ITSDs. After the test is completed in PITSD, the experiments in AITSD were followed for the respective samples.

(a) (b)

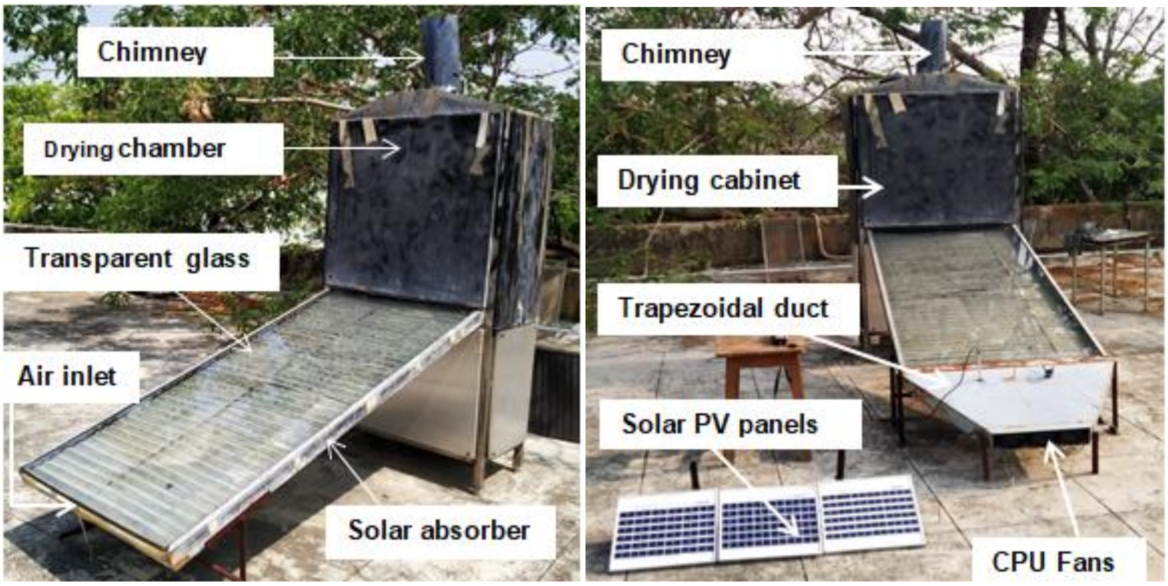
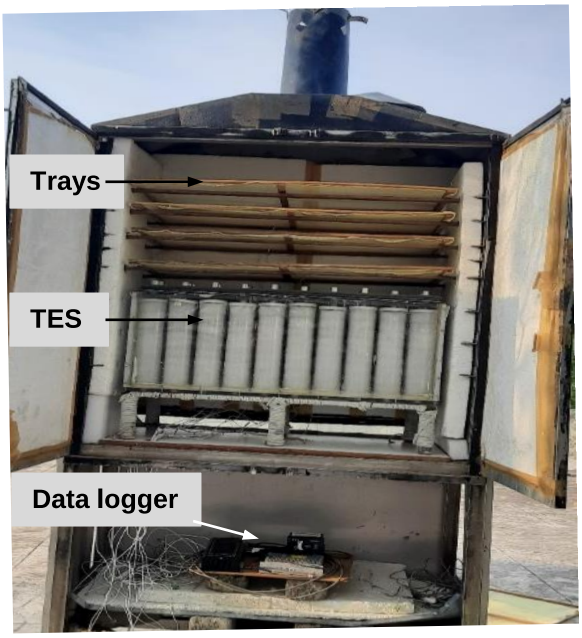


Fig. 3.2. Experimental setup of (a) passive) and (b) active indirect type solar dryer

Similarly, the setups for with TES were established from the same setups (respective passive and active). The passive and active setups were restructured with a rectangular framed TES unit with paraffin wax (no caking, CAS No. : 8002-74-2, EC No. : 232-315-6, congealing point: 56-60 ^{o}C, IMEDIA, India) as a phase changing material (PCM). The setup with TES has a separate PCM unit which consists polycarbonate tubes (5×10=50) with concentric fins made by aluminium placed inside drying section just below the bottom tray as mentioned in **Fig. 3.3 (a)**. The diagram of a single PCM cell is also represented in Fig. **3.3 (b)**.

(a)



(b)

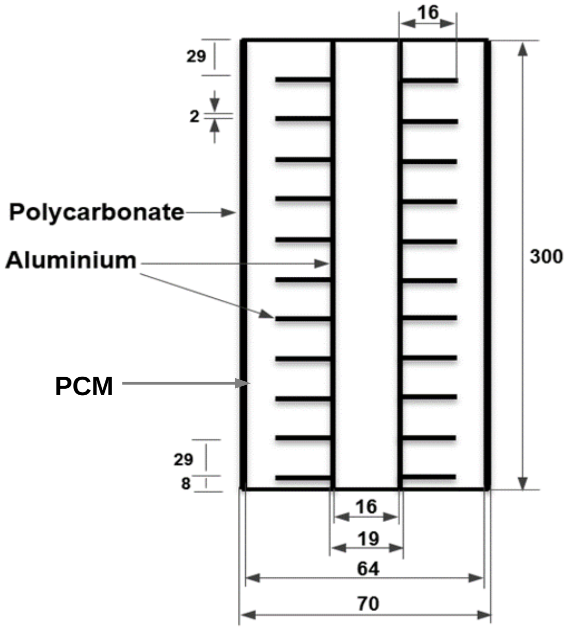


Fig. 3.3. (a) Photograph of rear view of the setup with TES (b) diagram of PCM single cell

3.4. Components of ITSD and their specifications

In this section, the basic components of the ITSD and their precisions are presented in **Table 3.1** below.

Table 3.1. Components of ITSD and their specifications

No	Components	Specifications
1	3 Solar PV panels	Solar PV panels (10W each)
2	3 CPU fans	CPU fans (12V each)
3	Collector tilt angle	30° S (with horizontal)
4	Overall dimensions of SAC	2 m × 1.05 m × 0.125 m
5	Glazing material	Window glass
6	Dimensions of drying chamber	0.85 m × 0.4 m × 1.05 m
7	Thickness of glass	5 mm
8	Mode of air flow	Passive and active air flow
9	Absorber plate	2 m × 0.9 m of corrugated V-shape with black colour coating
10	Material for tray	Wood framed plastic mesh

11	TES	Paraffin wax (no caking, CAS No. : 8002-74-2, EC No. : 232-315-6, congealing point: 56-60 °C, IMEDIA, India)
12	PCM cell	Polycarbonate tube, Al fins

3.5. Materials used and their specifications

A hot air oven (PPI, Unix96, made in India) (**Fig. 3.4 a**) was used to evaluate the initial MC of the samples. Digital weighing balance (OHAUS, PAG24, 8-1415VAC, 50/60 Hz, readability-0.0019, USA) (**Fig. 3.4 b**) was employed to measure the mass of the samples. The 16 channel loggers, PPI, made in India (**Fig. 3.4 c**) was used to record and store the temperature, relative humidity, and velocity. Humidity transmitter (Testo635, made in India) (**Fig. 3.4 d**) and RTD sensors (**Fig. 3.4 e**) have been employed to record the temperature and relative humidity during the experiments. The fruit pillars and knives (**Fig. 3.4 f**) were used to pill and slice the samples. More details on experimental setup and instruments used for experiments are summarized in **Table 3.2**.

(a) (b) (c)

(d) (e) (f)

Fig. 3.4. Photo snapshot of (a) digital weighing balance, (b) hot air oven, (c) data logger, (d) humidity transmitter, (e) RTD sensor and (f) knives and fruit pillars

Table 3.2. Materials used in experimental and their accuracy

Name of instrument	**Model and brand**	**Specification**	**Accuracy**
Solar power meter	Tenmar TM 207-Taiwan	0-200 W/m^2 -20 to 80 °C	±10 W/m^2
Solar PV panel	S1012, Access solar limited	10W, 17V, 0.699A	-
Electronic weighing balance	OHAUS PA 214, USA	0-200 g	± 0.2 mg
RTD Pt-100 sensor	PPI made in India	0-40 °C	±1 °C
Humidity transmitter	RH-33, PPI-Taiwan	0-100%	± 2% RH
Hot wire anemometer	Tenmar, TM 4002	0-80% RH 0 to 2 m/s -40 to 85 °C	± 3% RH
16 channel loggers	PPI, Made in India	-	± 25%
Fans	9P 12H	DC, 12V, 0.25A, 45±°C	-
Hot air oven	PPI, made in India	230V, 3500W,15A, 0-250 °C	-

3.6. Procedures involved during experiments

Initially, passive experiments were done. Later, the trapezoidal duct, three fans and solar PV panels were installed for conducting active setups experiments. Similarly, after running the tests in the setups without TES, the experiments in the setups with TES are followed for every sample. Fresh ivy gourds, pineapple, and carrot were bought from a local market in Warangal, Telangana, India on their respective experiment dates. Ivy gourd and carrot have been washed with clean water, and pineapple's spiky outer layer has been removed so that unwanted materials and dust were removed from the surface. They were sliced into a 5 mm thick cylindrical shape using a vegetable cutter. For each test, a total of 800 g ivy gourd, pineapple, and carrot slices were placed on the trays inside the drying chamber (200 g × 4 trays) as shown in **Fig. 3.5 (a), (b),** and **(c),** respectively. The experiments were performed from 8:00 to 18:00 h for without TES setups, and from 8:00 to 24:00 for with TES setup. Solar radiation, temperature, relative humidity, air velocity, and mass loss data was recorded at every 1 hour of the experiment duration. The drying kinetics, the performance parameters, and 3E indicators of drying the samples were estimated for both passive (with and without TES) and active (with and without TES) experiments. The final dried products of ivy gourd, pineapple, and carrot are displayed in **Fig. 3.6 (a), (b),** and **(c)**, respectively.

After making sure that all the RTD sensors (placed on the trays, inlet and outlet of the collector, in five equal distances inside the TES) were working properly, they were connected to data logger. The back door of drying section have been opened and closed to place the samples and to measure the mass of the samples. The mass of the sample have been recorded at every hour. The active setup provisions (at the collector inlet of passive indirect solar dryer) and TES units (inside the drying section just below 1st tray) were removed and installed for their respective turn of the experiments.

(a) (b) (c)

Fig. 3.5. Photo snapshot of fresh sliced (a) ivy gourd (b) pineapple and (b) carrot on trays

(a) (b) (c)

Fig. 3.6. Photo snapshot of dried slices of (a) ivy gourd (b) pineapple and (b) carrot on trays

3.7. Determination of initial moisture content

The initial MCs (MC_i) of the samples (ivy gourd, pineapple, and carrot) were evaluated by keeping 12 sample slices of each samples in a hot air oven for 24 h after maintaining at temperature of 105 °C. The estimation was carried out for five random slices of ivy gourd, pineapple, and carrot sliced as summarized in **Tables 3.3**, **3.4** and **3.5**, respectively. The samples were weighed before and after drying by using digital weighing balance. The MC was estimated using,

$$MC = \frac{m_{i-}m_f}{m_{i/f}} \times 100 \quad (1)$$

Where, *m* is mass of sample, the subscripts *i* and *f* are initial and final.

Table 3.3. Initial moisture content of the ivy gourd slices

Sl No:	Initial mass (m_i), kg	Final mass (m_f), kg	Initial moisture content	
			MC_{wb} (kg/kg of wb)	MC_{db} (kg/kg of db)
1	0.0032	0.1935×10^{-3}	93.929	15.473
2	0.0024	0.1493×10^{-3}	93.841	15.236
3	0.0035	0.2118×10^{-3}	94.055	15.822
4	0.00354	0.2201×10^{-3}	93.776	15.068
5	0.00326	0.2035×10^{-3}	93.756	15.0172
Average			**93.8714**	**15.323**

Table 3.4. Initial moisture content of the pineapple slices

Sl No:	Initial mass (m_i), kg	Final mass (m_f), kg	Initial moisture content	
			MC_{wb} (kg/kg of wb)	MC_{db} (kg/kg of db)
1	0.0216	0.00243	88.75	7.89
2	0.0242	0.00285	88.26	7.52
3	0.0207	0.00215	89.66	8.67
4	0.0266	0.00283	89.36	8.4
5	0.0229	0.00284	87.63	7.09
Average			**88.73**	**7.91**

Table 3.5. Initial moisture content of the carrot slices

Sl No:	Initial mass (m_i), kg	Final mass (m_f), kg	Initial moisture content	
			MC_{wb} (kg/kg of wb)	MC_{db} (kg/kg of db)
1	6.1272	0.6069	90.10	9.10
2	5.7115	0.5666	90.08	9.08
3	5.8501	0.5761	90.15	9.16
4	4.927	0.4846	90.16	9.17
5	6.5262	0.6434	90.14	9.14
Average			**90.13**	**9.13**

3.8. Equations employed

3.8.1. Energy and performance parameters estimation

The principle of mass conservation has been applied to evaluate the energy participated in every component of the dryer during the experiment

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{2}$$

Equation (2) denotes the mass balance and is employed to assess the energy participated in the experiment [77]. Similarly, the energy balance equation can be written as,

$$\sum \dot{E}_{\mathrm{i}} = \sum \dot{E}_{\mathrm{o}} \tag{3}$$

Where, *E* is for energy, subscripts *i* and *o* stand for entering into and leaving out of the system, respectively. The rate of net energy entering into a control volume through work done (*W*) and heat transfer (*Q*) is equal to the net energy through mass [139]. Assuming that work done by the dryer is zero and the variations of potential and kinetic energies are negligible,

$$Q - W = \sum \dot{m}_{ai}\left(hs_{ai} + \frac{v^2{}_{ai}}{2} + x_i g\right) - \sum \dot{m}_{ao}\left(hs_{a0} + \frac{v^2{}_{ao}}{2} + x_o g\right) \tag{4}$$

Where, *v* represents velocity, *hs* is for specific enthalpy and *x* stands for the air datum height.

3.8.1.1. Energy of collector

Energy received by the collector [143] is calculated by,

$$Q_{ic} = I A_c \tag{5}$$

$$Q_a = \dot{m} c_{\mathrm{pa}} (T_{co} - T_{ci}) \tag{6}$$

Q_{ic} is useful heat input; Q_a is heat outflow of collector or actual heat supplied; *I* stands for solar radiation intensity (W/m^2) and A_c is the area of collector (A_c =1.8 m^2).

The efficiency of the collector (η_c) is,

$$\eta_c = \frac{Q_a}{Q_{ic}} = \frac{\dot{m}\, c_{\mathrm{pa}} (T_{co} - T_{ci})}{I\, A_c} \tag{7}$$

3.8.1.2 Energy of drying section

The energy participated in the drying cabinet and dryer efficiency (η_d) during the tests are,

$$E_{in} = I_a\, A\, t_d \tag{8}$$

$$\eta_d = \frac{m_w\ h_w}{I_a\, A} \tag{9}$$

Where, E_{in} is input energy (kWh), I_a is average solar energy within the total duration for the test (kW/m^2), *A* is all area for the drying object exposed to solar flux (m^2), t_d stands for the total time (h), m_w represents the mass of moisture removed (kg) and h_w stands for the latent heat (kJ/kg).

SEC (kWh/kg) and SMER (kg/kWh) were estimated using [8],

$$SEC = \frac{E_{in}}{m_w} \quad (10)$$

$$SMER = \frac{m_w}{E_{in}} \quad (11)$$

3.8.2. Estimation of drying kinetics

The D_e was estimated using the experimental data. The expression used [30, 95, 112] is,

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \pi^2 \frac{D_e}{4L^2} t \quad (12)$$

Where, t is total time of drying and L is the thickness of the sample slices.

The activation energy (E_a) was calculated using the Arrhenius equation [96],

$$D_e = D_o \exp(-\frac{E_a}{RT}) \quad (13)$$

Where, D_o (m^2/s) is the pre-exponential factor and R (J/mol K) is the universal gas constant.

Moisture ratio (MR) was calculated by using [34],

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} \quad (14)$$

Where, the suffixes t, e and i mention the instantaneous, equilibrium and initial. Eq. (14) can be approximated as,

$$MR = \frac{MC_t}{MC_i} \quad (15)$$

And the drying rate (DR) (kg/h) can be estimated using,

$$DR = \frac{MC_t - MC_{t+dt}}{dt} \quad (16)$$

Where, dt is change in time.

Mass transfer coefficient (h_m) was estimated [116] using,

$$h_m = \frac{V}{AL} ln(MR) \quad (17)$$

Where, V (m^3) is volume of the sample, A (m^2) total exposed area of sample and L (m) thickness of the sample.

The heat transfer coefficient (h) can be estimated [118] using,

$$h = h_m \frac{k}{D_{ab} Le^{1/3}} \quad (18)$$

where, D_{ab} (m^2/s) water moisture diffusivity in air (0.282×10^{-4} m^2/s), k (W/m K) is thermal conductivity of air and Le is Lewis number which defines the relation between thermal and concentration boundary line thickness and it is expressed as,

$$Le = \frac{\alpha}{D_{ab}} \quad (19)$$

Where, α (m^2/s) is drying air thermal diffusivity.

3.8.3. Evaluation of 3E parameters

3.8.3.1. Exergy evaluation

Exergy is the quality of energy available in a system, which can be evaluated by applying the 2nd law of thermodynamics. It traces the quality of available entropy (S), workflow, internal energy (u), momentum, radiation and chemical energies participated in drying during the experiment. The general expression to evaluate the exergy [139] is,

$$EX = (u - u_o) + T_o(S - S_\infty) + P_o(V - V_\infty) + \frac{v^2}{2} + g_o(x - x_\infty) + \sum_{ch}(\mu_{ch} - \mu_\infty)M_{ch}$$

$$+ \sigma A_i F_i(3T^4 - T_\infty^4 - 4T_\infty T^3) \quad (20)$$

Where, μ is chemical potential (kJ/mol), M is mole number, F is shape factor and the subscripts ∞ and *ch* stand for surrounding environment and chemical, respectively.

While performing the evaluation for exergy, the following points were assumed: a steady flow analysis is used. Due to minimal temperature variations between the dryer and surrounding, radiation energy is considered to be negligible. The gravitational, chemical and momentum energies are also considered to be negligible. Pressure variation in the system and the loss of exergy by the product were ignored. Hence, Eq. (20) is transformed into,

$$\dot{EX} = \dot{m}\, c_{pa}\left[(T - T_a) - T_a \ln\left(\frac{T}{T_a}\right)\right] \quad (21)$$

Where, T_a describes the temperature of ambient air.

Exergy on the solar collector

Exergy on solar collector [68] is expressed by,

$$\sum EX_{in\_c} - \sum EX_{out\_c} = \sum EX_{l\_c} \quad (22)$$

Where, the first, second and third sum expressions in Eq. (22) are inflow, outflow and loss of exergy of solar collector, respectively.

Exergy inflow is related to the solar radiation [81] as mentioned below,

$$\sum EX_{in\_c} = \left[1 - \frac{T_a}{T_r}\right] Q_{in\_c} \quad (23)$$

Where, T_r is the sun temperature (6000 K).

$$Q_{in\_c} = \alpha\tau I_r A_c \tag{24}$$

Q_{in_c} stands for the solar radiation on the surface of the collector plate. The absorptivity (α) and transmissivity (τ) for the window glass are 0.95 and 0.8, respectively [80].

Exergy outflow and exergy loss of the collector [42] are evaluated using,

$$\sum EX_{out\_c} = \dot{m}_{\mathrm{a}} c_{\mathrm{pa}} \left[(T_{co} - T_{ci}) - T_{\mathrm{o}} \ln\left(\frac{T_{\mathrm{co}}}{T_{ci}}\right) \right] \tag{25}$$

$$\sum EX_{l\_c} = T_o S_{gen} = \left[1 - \frac{T_o}{T_r}\right] \dot{Q}_{in\_c} - \dot{m}_{\mathrm{a}} c_{pa} \left[(T_{co} - T_{ci}) - T_{\mathrm{o}} \ln\left(\frac{T_{\mathrm{co}}}{T_{ci}}\right) \right] \tag{26}$$

Exergy efficiency for the solar collector is calculated by,

$$\eta_{EX\_c} = \frac{\dot{EX}_{out\_c}}{\dot{EX}_{in\_c}} = 1 - \frac{\dot{EX}_{l\_c}}{\dot{EX}_{in\_c}} = 1 - \frac{T_a S_{gen}}{\left[1 - \left(\frac{T_a}{T_r}\right)\right] \dot{Q}_{in\_cp}} \tag{27}$$

Exergy on the drying section

The exergy of the drying section can be evaluated from the basic concept of exergy balance, which can be explained as exergy loss equivalent to the difference between exergy inflow and outflow, therefore,

$$\sum EX_{in\_d} - \sum EX_{out\_d} = \sum EX_{l\_d} \tag{28}$$

Where subscript *d* is drying section, while, exergy inflow and outflow [68, 79] can be written as,

$$\sum EX_{in\_d} = \dot{m}_{\mathrm{a}} c_{pa} \left[(T_{di} - T_{\mathrm{a}}) - T_{\mathrm{a}} \ln\left(\frac{T_{di}}{T_a}\right) \right] \tag{29}$$

$$\sum EX_{out\_d} = \dot{m}_{\mathrm{a}} c_{pa} \left[(T_{do} - T_a) - T_{\mathrm{a}} \ln\left(\frac{T_{do}}{T_a}\right) \right] \tag{30}$$

Where, T_{di} and T_{do} are inlet and exit temperature of drying section, respectively.

The exergy efficiency of the drying section can be evaluated by dividing exergy outflow by inflow of the drying section. It is mentioned as,

$$\eta_{EX\_d} = \frac{\dot{EX}_{out\_d}}{\dot{EX}_{in\_d}} \tag{31}$$

Estimating sustainability indicator of the exergy

The exergy losses and irreversibility of a process can be evaluated through the sustainability indicators of exergy such as waste exergy ratio (*WER*), improvement potential (*IP*), sustainability indicator (*SI*), and environmental impact factor (*EIF*). They portray sufficient evidence about the thermodynamic performance and sustainability of a system. *WER* and *IP* are positively related to exergy loss, whereas SI is negatively related to exergy loss. [79, 139].

$$WER = \frac{\dot{EX}_l}{\dot{EX}_{in}} \tag{32}$$

$$IP = (1 - \eta_{EX})\dot{EX}_l \tag{33}$$

$$SI = \frac{1}{1-\eta_{EX}} \tag{34}$$

$$EIF = WER \frac{1}{\eta_{EX\_d}} \tag{35}$$

3.8.3.2. Economic analysis

Making an economic analysis for a solar dryer makes it to be affordable and well known to the public. The main parameters to be considered during investigating the economic analysis of a system are capital cost (C_T), annual cost, payback period and savings earn for the total working lifespan. The following equations are employed to make and compare the economic analysis of PITSD (without and with TES) AITSD (without and with TES) [84, 139]:

$$C_T = C_{mt} + C_{lb} \tag{36}$$

Where, C_{mt}, and C_{lb} are the material and labor cost, respectively.

The yearly cost of the dryer (C_y) is evaluated using:

$$C_y = \left[C_T + \sum_{n=1}^{Ld} (C_{mn} + C_{opn})\, \beta^n\right] \left[\frac{\beta - 1}{\beta(\beta^{L_d} - 1)}\right] \tag{37}$$

Where, C_{mn} and C_{opn} (2% of C_T) are maintenance cost, operation cost at year *n*, respectively, and L_d the life of the dryer. And β is:

$$\beta = \frac{100 + i_d}{100 + i_f} \tag{38}$$

Where, i_d (%) is interest or discount, and i_f (%) is inflation.

The annual drying cost for each dried food (C_d) is determined by,

$$C_d = \frac{C_y}{Q_{dry}} \tag{39}$$

$$Q_{dry} = Q_h D_h \tag{40}$$

Where, q_{dry}, q_h and D_h represent the amount of dried product, quantity of dried material per hour and total hours of sunshine in a given year, respectively.

The yearly savings (SV) can be calculated from:

$$SV = q_{dry}P_{dry} - q_{fresh}P_{fresh} - q_{dry}C_d \tag{41}$$

Where, P_{dry}, P_{fresh}, and q_{fresh} stand for the price of dry product, price of fresh product and quantity of fresh produce used per year, respectively.

The payback period (N) for the dryer considering i_d = 7.6% and i_f = 4.54% [139, 141] is estimated using:

$$N = \frac{ln\left(1 - \frac{C_T}{SV}(i_d - i_f)\right)}{ln\left(\frac{1+i_f}{1+i_d}\right)} \tag{42}$$

3.8.3.3. Environmental impact analysis

The environmental issue should be a top priority while studying the feasibility of a system before implementation. Hence, the influence of dryers on the environment has been evaluated. The embodied energy (E_e) is the amount of total energy consumed to construct the dryer which included each component of the dryer.

Energy payback period (EPBP)

The time duration required to substitute all the energy that is used to construct a system (E_e) is termed as energy payback period (EPBP) [84] and expressed as:

$$EPBP = \frac{E_e\ (kWh)}{E_{AO}\ (kWh/year)} \tag{43}$$

The annual energy output of the dryer (E_{AO}) [9] is determined using:

$$E_{ao} = E_{DO} \times D_y \tag{44}$$

Where, D_y represents the total of active sunshine days in a year (240 days). The energy output of the solar dryer per day (E_{DO}) (kWh) [141] is described:

$$E_{DO} = \frac{m_w \times h_w}{3.6 \times 10^6} \tag{45}$$

CO_2 emission

A kWh of electricity production through coal is assumed to be equivalent to the mean emission of 0.89 kg of CO_2 [84]. E_e and L_d are the main influencing parameters while estimating the emission of CO_2 per year. It is evaluated using.

$$CO_{2\,em/yr} = \frac{0.98 \times E_e}{L_d} \text{ kg/year} \quad (46)$$

Losses like transmission (L_t) and internal losses (L_z) can be considered in the real application, and hence, CO_2 emission per year is further expressed as [78],

$$Yearly\ CO_2\ emission = \frac{E_e}{L_d} \times \frac{1}{1-L_t} \times \frac{1}{1-L_z} \times 0.98 \text{ kg/year} \quad (47)$$

If the L_t = 40%, and L_z = 20% are taken, then Eq. (47) can be re-written as,

$$Yearly\ CO_2\ emission = \frac{E_e}{L_d} \times 2.042 \text{ kg/year} \quad (48)$$

Carbon dioxide (CO_2) mitigation and credit earned

The CO_2 mitigation [68] of the passive ITSD (kg) is calculated using,

$$CO_2\ mitigation = (E_{AO} \times L_d - E_e) \times 2.042 \quad (49)$$

Carbon credit earned is estimated [18] using,

$$Carbon\ credit\ earned = CO_2\ mitigation \times price\ per\ tonne \quad (50)$$

3.9. Uncertainty analysis

The root-sum square method [144] has been applied to evaluate the uncertainty of the experimental and estimated data. Uncertainties of independent and dependent variables of these experiments were estimated as:

$$Y = \left[\left(\frac{\partial J}{\partial a_1} a_1\right)^2 + \left(\frac{\partial J}{\partial a_2} a_2\right)^2 + \left(\frac{\partial J}{\partial a_3} a_3\right)^2 + \cdots + \left(\frac{\partial J}{\partial a_i} a_i\right)^2\right]^{0.5} \quad (51)$$

Where, Y designates uncertainty; J represents the estimated value of a variable and a_i stands for the uncertainty of the measured parameters.

3.10. Materials properties used for the estimation

Material properties considered during the analysis are described in **Table 3.6**.

Table 3.6. Materials properties used for the analysis

Properties	Designation (symbol)	Unit	Value	Reference / Remarks
Thermal conductivity of air	k	W/mK	0.02848	[115]
Air density	ϱ	Kg/m^3	1.098	
Specific heat of air	c_p	kJ/kg	1005	
Lewis number	Le	-	0.673759	[145]
Latent heat of water	L_w	J/gK	2346.4	[146]
Radius of the sample	R	m	-	Measured
Thickness of sample	L	m	0.005	[92]
Mass flow rate (PITSD)	$\dot{m}$	Kg/s	0.043	Calculated
Mass flow rate (AITSD)	$\dot{m}$	Kg/s	0.073	Calculated
Air inlet area	A_i	m^2	0.054	Measured
Collector area	A_c	m^2	1.8	Measured

Chapter 4

Results and discussions

Chapter 4

4. Results and discussions

4.1. Introduction

In this **chapter**, the results and discussions are presented. The development of active mode provision is discussed. The performance parameters of PITSD and AITSD without and with TES are elaborated. The drying kinetics of the samples (ivy gourd, pineapple, and carrot) are described in detail. Furthermore, the exergy parameters, environmental impact indicators, and the economic importance are discussed and presented. Finally, the overall performance of PITSD (with and without TES) and AITSD (with and without TES) was comprehensively compared and analyzed. Moreover, it is important to mention that to reduce the bulkiness of the results contents, only graphs of ivy gourd drying data are demonstrated in this chapter. However, data of the samples are clearly addressed in the content.

4.2. Development of active mode provision

An active mode provision was developed and fitted in the air inlet of PITSD to encourage the velocity of drying air. It was manufactured using a trapezoidal duct as diagrammatically shown in **Fig. 4.1.** The components of the developed active mode provision are, three CPU fans (12 V each) (**Fig. 4.2 a**), three PV panels (10 W each) and the trapezoidal duct (**Fig. 4.2 b**). Both CPU fans and PV panels were purchased from the Warangal local market and the trapezoidal duct was manufactured in a local fitter shop. Finally, all the parts were integrated to form AITSD and made ready to perform active mode drying experiments.

Accordingly, the developed setup could easily be constructed from the available materials with a minimum cost to perform the active mode experiments. Notably, the structure of the trapezoidal duct can be flexibly manufactured in accord with the design of the existing setup (PITSD). It didn’t take much energy to install, and was easy to perform suitably all the active drying experiments. It is also easy to operate so that any unskilled man can perform the drying process. Hence, it would be recommended to optimize the design parameters so that will be applicable for furtherance and implementations in primitive (less privileged) areas.

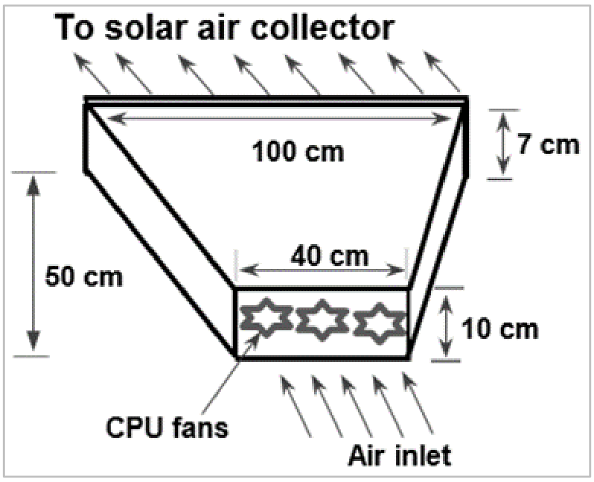


Fig. 4.1. Diagrammatic representation of trapezoidal duct

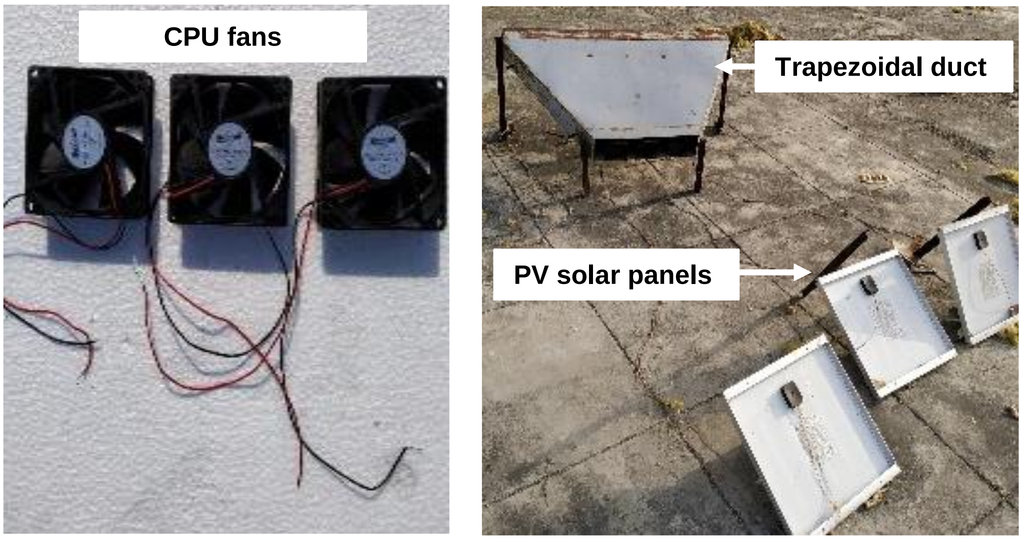


Fig. 4.2. Photo snapshot of (a) CPU fans and (b) trapezoidal duct and PV solar panels

4.3. Indirect type solar dryer (ITSD) without TES

4.3.1. Solar radiation data

Solar radiation was recorded for the consecutive days during drying of ivy gourd, pineapple, and carrot in passive and active ITSDs. The solar radiation data for the drying dates of ivy gourd is shown in **Fig. 4.3**. The reading was started at 8:00 h and completed at 18:00 h (for all the three samples drying dates) which are represented as 0 h and 10 h, respectively, in the X-axis of **Fig. 4.3**. The minimum values of solar radiation were observed to be 178 and 184 W/m^2 and the maximum values were recorded to be 990 and 1020 W/m^2 for passive and active setups, respectively. The average radiations were recorded to be 662.9 and 669.75 W/m^2 for the passive and active modes, respectively. It shows that on both days, almost equal solar intensity was observed. In the same way, the solar radiation for drying dates of pineapple was recorded. The average and maximum values of solar radiation were 654.4 and 658.5 W/m^2, and 963 and 1015 W for passive and active setups, respectively. The variation in average radiation was noticed to be 4.1 W/m^2 which is negligible to consider that the radiation difference might induce variations in other drying parameters.

Similarly, minimum and maximum solar radiation recorded during drying carrot in passive setup was 173 and 963 W/m^2, while the same for active setup was 188 and 993 W/m^2, respectively. For the passive and active setups, the average values were 649.75 and 660.3 W/m^2, respectively. The average variation is noticed to be negligible (9.75 W/m^2).

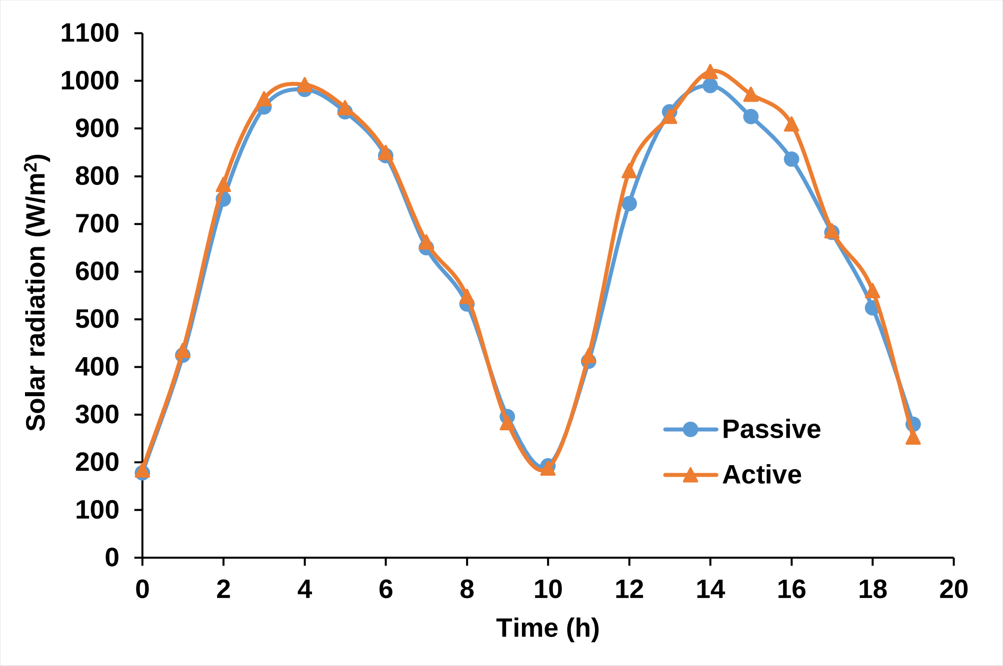


Fig. 4.3. Solar radiation for passive and active mode drying experiments of ivy gourd

4.3.2. Performance parameters

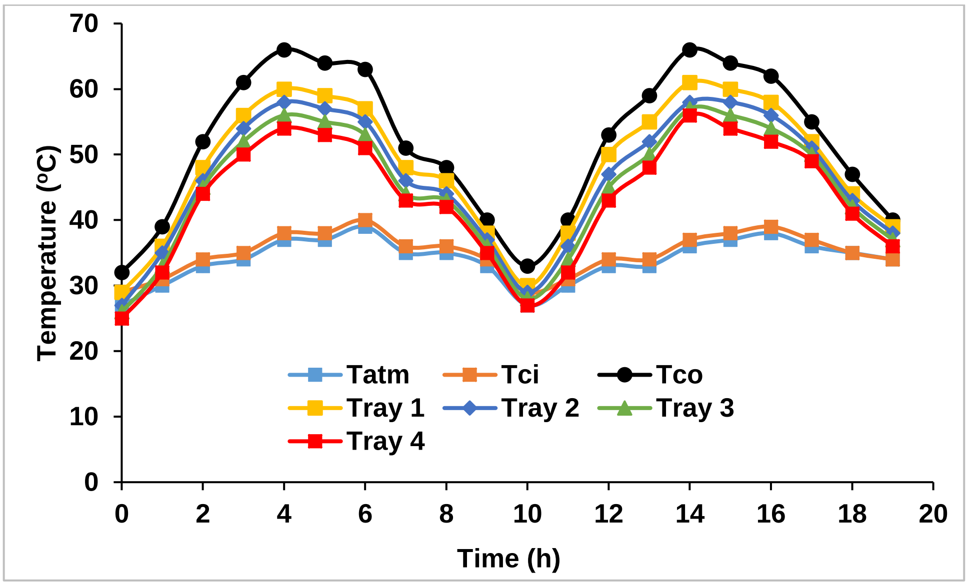
4.3.2.1 Temperature distribution

The temperature distributions on solar collector inlet (T_{ci}), outlet (T_{co}), on trays 1 - 4 (T_1, T_2, T_3, and T_4), and ambient temperature (T_{atm}) have been recorded hourly and shown in **Figs. 4.4 (a) and (b)** (for ivy gourd drying) for the passive and active setups, respectively. On the drying dates of ivy gourd, the minimum T_{co} was 32 and 31 °C for the passive and active while 66 and 62 °C were their respective maximum records of same. The average T_{co} found to be 51.7 and 48.5 °C for the passive and active setups, respectively. And again, the temperatures in the drying chamber (T_d) (the average of 4 trays) have been recorded as 25 °C (minimum), 64 °C (maximum) and 45.7 °C (average) for the passive and 27 °C (minimum), 59 °C (maximum) and 44.2 °C (average) for the active setup. The temperature readings were seemed to be lower in active setup than in passive because of faster transportation of heat by the enhanced air velocity by the CPU fans provided in active ITSD setup.

And again, for pineapple drying dates, the transient temperature has been recorded evaluated (Figs. not shown here). The maximum T_{atm}, T_{ci}, T_{co} and T_d of the passive setup was 43.4, 44, 81, and 69 ^oC, respectively. The same for the active setup was 41.8, 42, 69 and 59 ^oC, respectively. The average T_a, T_{ci}, T_{co} and T_d for passive setup were 38.48, 39.1, 62.9, and 51.39 ^oC, respectively. The same for the active one were 36.66, 37.55, 55.1 and 47.43 ^oC, respectively. The average temperature in passive is recorded to be higher than the active setup. The reason for the variation could be the promoted air velocity in the active setup which might have transported heat with a fast rate lowering the temperature.

On the same ways, for carrot drying dates, the minimum T_{co} reached 35 and 29°C for the passive and active, respectively, while the maximum records for the same were 75 and 66°C. Passive setup had an average T_{co} of 61.2 °C, while the active had 53.1 °C for the same. The average, minimum and maximum T_d of the passive setup was 51, 27, and 69 °C, respectively, while the same for the active was 45.6, 25, and 61 °C, respectively. The temperature was lower in active setup because of the higher air velocity provided by the CPU fans reducing air stagnant time in the air passage compared to passive setup.

(a)



(b)

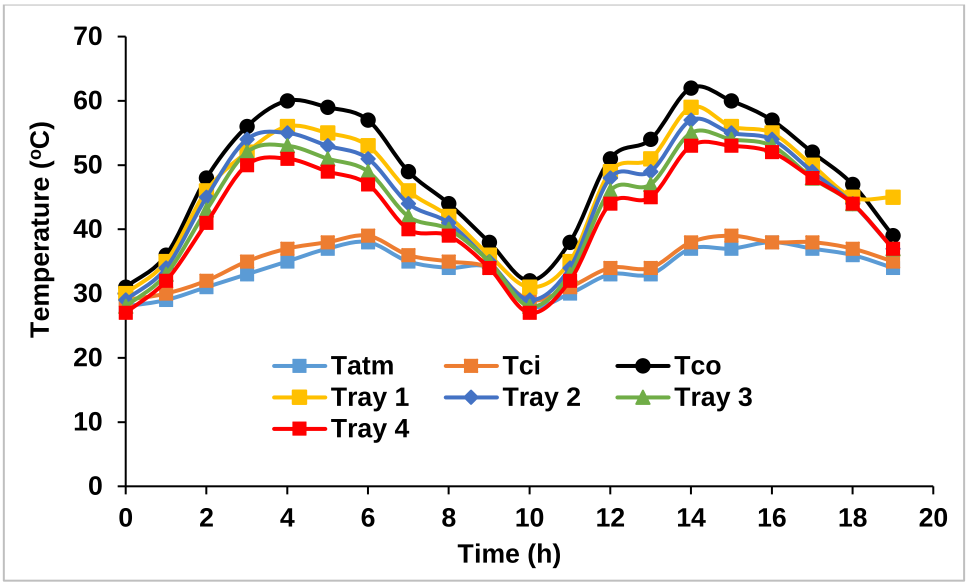


Fig. 4.4. Temperature distribution in (a) passive (b) active ITSD during drying ivy gourd

4.3.2.2. Actual heat supply (Q_a)

Figure 4.5 shows the Q_a for both passive and active setups during drying ivy gourd; but not shown here for the other two samples. The Q_a for the active setup is greater than that of passive setup. The Q_a is a function of the mass flow rate where the more mass flow rate is there in the active setup because of CPU fans which resulted in higher Q_a. The average Q_a was estimated to be 776.66 and 997.76 W for the passive and active setups, respectively, while 138.69 and 146.73 W were their respective minimum recordings for the same. The maximum Q_a for both passive and active setups were found to be 1340.67 and 1760.76 W, respectively. The variations happen because of the variations of mass flow rate for the respective setups. From this, it is inferred that active setup performed well compared to passive setup.

Similarly, the Q_a of the two setups during drying pineapple was estimated using Eq. (6). Q_a noticed to be varying in line with the change of solar flux for both setups. The maximum Q_a for the passive and active setups was 1069.32 and 1282.38 W, respectively. The average values for the same were estimated to be 704.25 and 789.38 W, respectively. Active setup showed an improvement of 12.1 % (85.18 W) in average Q_a compared to passive, which could because of the fostered air velocity in the passive setup.

Furthermore, the Q_a to passive and active setups during the drying of carrot was also estimated. The passive and active setups had an average Q_a of 705.64 and 789.55 W, respectively, while their respective minimum values were 130.65 and 256.28 W. On the other hand, the maximum

Q_a for the passive was 1056.64 W, and for active was 1238.66 W. The active setup has a considerably higher Q_a than the passive setup. These variations are due to mass flow rates varying between the setups. As a result, active setup appeared to work better than passive setup.

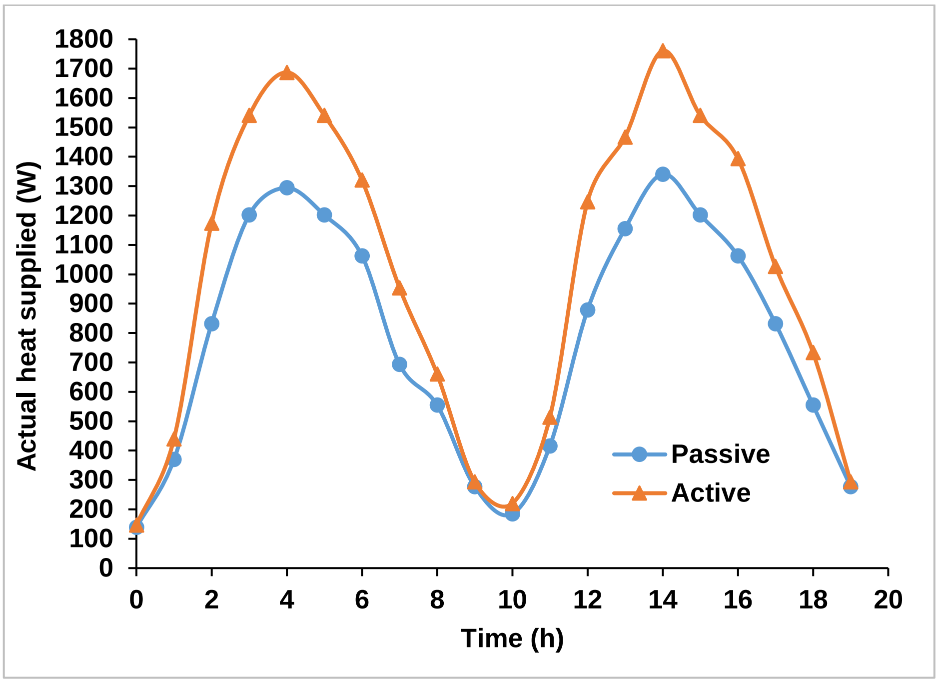


Fig. 4.5. Actual heat supply of passive and active ITSD during drying ivy gourd

4.3.2.3. Collector efficiency (η_c)

The η_c of the passive and active setups during drying the samples (ivy gourd, pineapple, and carrot) was calculated. The η_c for the pineapple drying is shown in **Fig. 4.6**. In both drying days of ivy gourd, the η_c was maximum at noon as there is good solar radiation at noon. The maximum, minimum and average η_c values for the passive ITSD (**Fig. 4.6**) were observed to be 75.2, 43.2 and 62.6 %. The same for the active setup were 94.5, 44.3 and 77.2%, respectively. An improvement of 23.4 % was noticed on the average η_c of active setup compared to passive ITSD.

Additionally, the η_c was determined from the temperature data measured during drying pineapple in passive and active setups. The estimated η_c was in the range of 38.48 – 92.47% for the passive and 40.72 – 95.54% for the active setups. The average η_c for the passive and active setups was 60.72 and 68.41%, respectively. In comparison with the passive, the active setup showed an improvement of 12.67% in η_c that could be because of the mass flow rate introduced in active ITSD.

Moreover, η_c of both setups during drying carrot has been evaluated. Accordingly, passive setup showed minimum, maximum, and average η_c values of 35.21, 76, and 56.86%, respectively. Similarly, for the passive setup, the same were 46.21, 88.2, and 68.74%, respectively. In comparison with the passive, the active setup demonstrated a 17.31% improvement in η_c. Hence, the active ITSD showed better performance than passive in η_c.

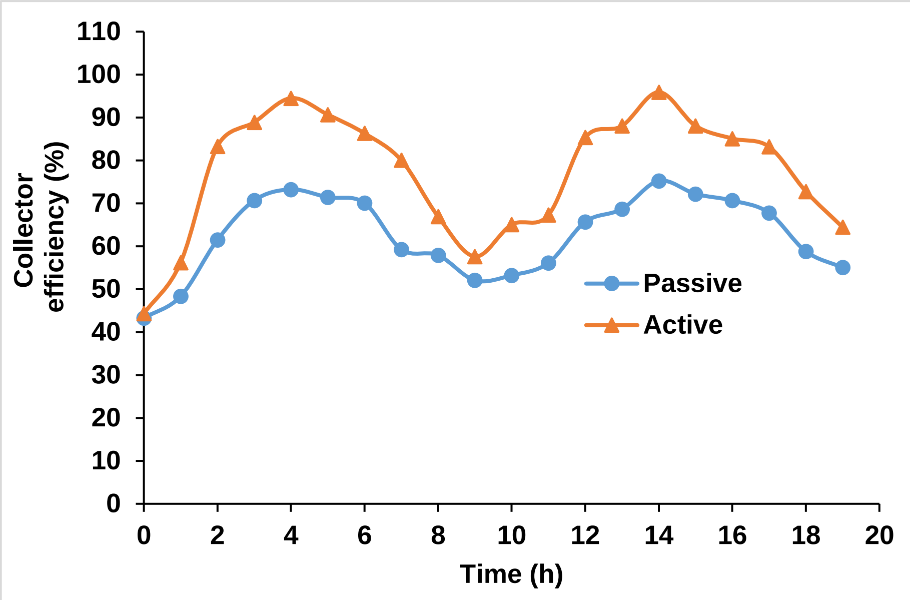


Fig. 4.6. Collector efficiency of passive and active ITSDs during ivy gourd

4.3.2.4. Drying efficiency (η_d)

The η_d of the ITSD has been evaluated for the passive and active setups from the recorded data of mass of water removed and solar radiation during drying ivy gourd, pineapple, and carrot slices. The η_d for the ivy gourd drying is represented in Fig. 4.7. From the estimated data of ivy gourd, the η_d of 6.12 and 17.45 % were the average and maximum for the passive setup, and the same was 7.8 and 17.96 % for the active setup, respectively. It shows that there is a 14.71% improvement of η_d in the active setup. Similarly, for pineapple drying, the estimated values show that the average η_d for the passive and active setups is 6.92 and 7.61%, respectively. There was a 10.01% improvement in η_d by using the central processing unit fans to promote air velocity in case of active setup. Moreover, during carrot drying, passive setup showed average and maximum η_d of 7.5 and 23.66%, and the same for the active setup were 9.55 and 32.29%, respectively. In the case of active setup, η_d is improved by 27.33% compared to passive setup.

Generally, the η_d is noticed to be increasing with an increasing rate at the first phase of the drying for both setups. After achieving maximum at noon, η_d started to decrease for the remaining drying duration. But the curve of η_d behaved to be flattening near the end of the drying. This is because, at the first stage of drying, there is much moisture on the surface of the samples that needs less energy. But for the rest of the drying duration, as time goes, the moisture on the surface is less and found inside pores of the drying object requiring much energy to remove the water. And the active setup showed better result compared to passive ITSD in η_d.

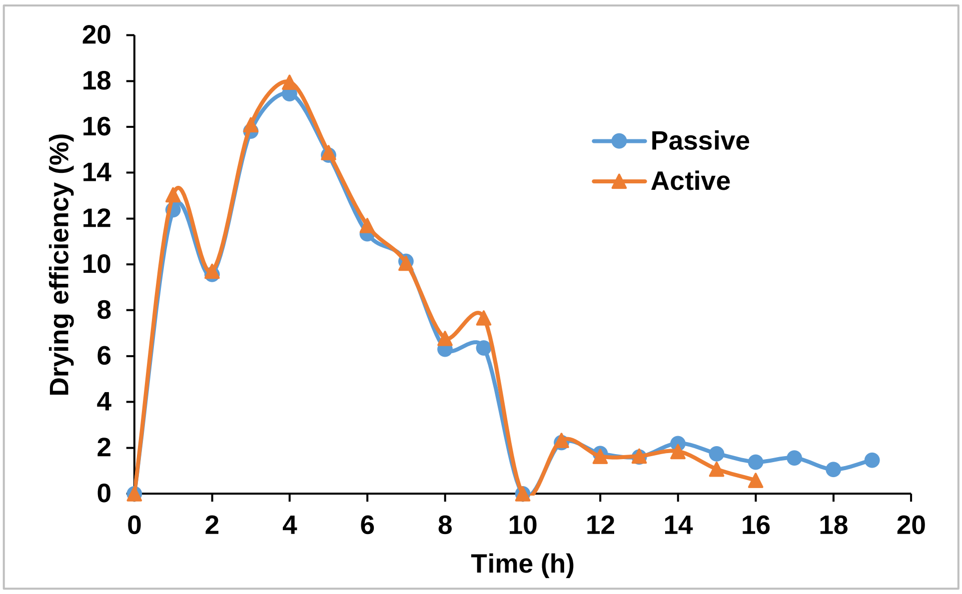


Fig. 4.7. Drying efficiency of passive and active ITSDs during ivy gourd

4.3.2.5. Specific energy consumption (SEC)

The SEC and SMER were evaluated for passive and active ITSD in drying ivy gourd, pineapple, and carrot. The results for ivy gourd is displayed in Fig. 4.8. From the data of ivy gourd, the SEC was ranged in between 0.132 and 4.99 kWh/kg for the passive setup, and was in between 0.106 and 5.96 kWh/kg for the active setup. The average variation of the SEC between passive and active setups was computed to be 26.15 % with their respective averages of the same being 1.549 and 1.144 kWh/kg. Additionally, during pineapple drying, for the passive setup, the SEC was in the range of 2.441 and 2.441 kWh/kg, while for the active setup, it was between 1.671 and 7.413 kWh/kg. The average difference in SEC between passive and active configurations was calculated to be 67.52%, with averages of 4.843 and 1.573 kWh/kg, respectively. Moreover, the SEC for carrot drying was ranged between 0.19 and 15 kWh/kg for the passive setup, and between 0.14 and 12.85 kWh/kg for the active setup. The average values of SEC for the passive and active setups we 4.72 and 3.2 kWh/kg, respectively. There was a 32.2% improvement (reduction) in SEC in active compared to passive setup.

As can be noticed from **Fig. 4.8**, the SEC is minimum at the beginning of the drying, and then gradually started to increase with time until it attains the maximum for both setups. At the beginning of the drying, the moisture on the surface of the product could be removed with minimum energy. When drying goes further, the moisture from the inner part of the product diffuses to the outer surface. This process requires more energy and this is the reason the SEC increases when time goes. Also, the SEC was found to be higher for the second day compared to the first day. On the second day, the product lost much of its MC, at the same time, there is few water molecules trapped in the complex pores of the food. For releasing them, more energy is needed and therefore, the SEC is high on the second day. Moreover, SEC is noticed to be higher for the passive than that of active setup. This is because the SEC is the input energy divided by the mass of moisture removed, and the amount of moisture removed was higher for the active because of the higher velocity of hot air as compared to passive setup.

4.3.2.6. Specific moisture extraction rate (SMER)

The SMER was evaluated by dividing the mass of MC eliminated by the net energy supplied. It was evaluated for the three samples drying, but the plot is shown here for ivy gourd (**Fig. 4.8**). The average SMER for drying ivy gourd in the passive and active setups was 0.646 and 0.0.875 kg/kWh, respectively. There was an improvement of 35.45% in the active setup compared to passive setup. Additionally, the evaluated data for drying pineapple shows that the average SMER for the passive and active setups was 0.207 and 0.635 kg/kWh, respectively. There was an improvement of 0.428 kg/kWh in active setup compared to PITD. Similarly, SMER for drying of carrot has been estimated. Its average values for the passive and active setup are 0.212 and 0.312 kg/kWh, respectively. Active setup improved the SMER by 47.17% compared to passive ITSD.

Generally, as a higher mass flow rate of air was there in the active setup, there would be more MC removal in active than passive setup, resulting in a higher SMER for active than passive setup. As depicted in **Fig. 4.8**, the SMER decreases with the increment of drying time. And as the SMER is inversely related to SEC, all the descriptions of SEC stated above holds accordingly for SMER in the inverse way.

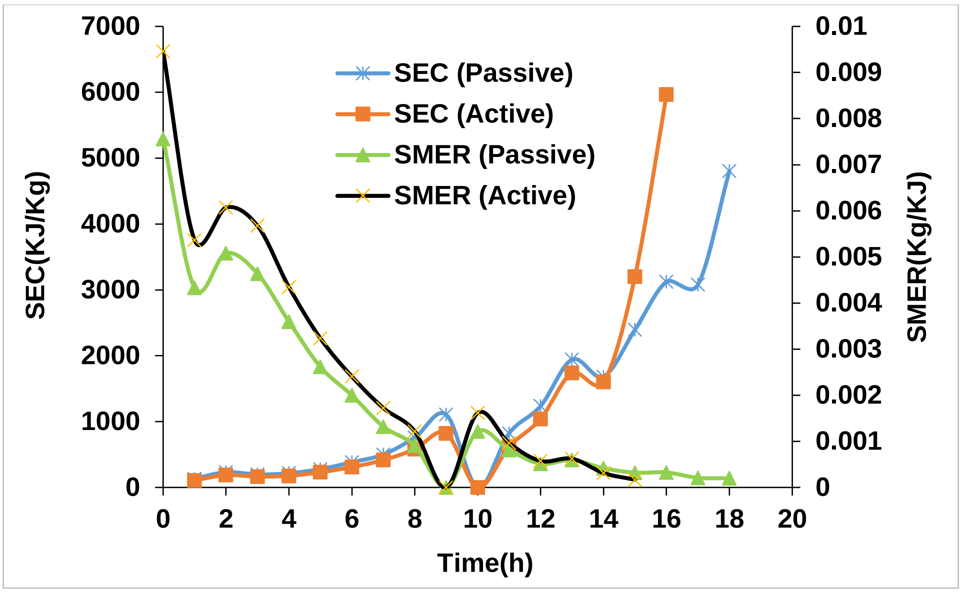


Fig. 4.8. SEC and SMER of passive and active ITSDs during ivy gourd

4.3.2.7. Comparative analysis of performance parameter of ITSD

In **Table 4.1**, for the passive and active setups, the results of performance parameters are summarized. Compared to passive setup, the active setup exhibited improvements for every variable measured/estimated for this study even though both setups received nearly equivalent radiation (approx.) for the drying days. Accordingly, as stated in **Table 4.1**, the average T_{co} and T_d were low in the active setup during drying the three samples. The Q_a for drying ivy gourd, pineapple, and carrot was improved by 28.47, 12.47, and 11.8%, respectively. The η_c for the same was improved by 23.4, 12.67, and 20.94%, respectively in the active setup compared to the passive setup. Similarly, there was 14.71, 10.01, and 27.33% improvement in η_d during ivy gourd, pineapple, and carrot drying, respectively. Furthermore, SEC and SMER were noticeably improved in the active setup. Hence, based on the results of the performance parameters, the active setup would be a promising setup.

Table 4.1. Comparison of the performance parameters of ITSD

Parameter	**Sample**	**Values**		**Difference (%)**	**Remark**
		Passive	**Active**		
Solar radiation (W/m^2)	Ivy gourd	662.9	669.75	1.03	-
	Pineapple	654.4	658.5	4.1	-
	Carrot	649.75	660.3	1.6	-
T_{co} (°C)	Ivy gourd	51.7	48.5	3.2 °C	Decreased

	Pineapple	62.9	55.1	7.8 ^{o}C	Decreased
	Carrot	61.2	53.1	8.1 ^{o}C	Decreased
T_d (^{o}C)	Ivy gourd	45.7	44.2	1.5 ^{o}C	Decreased
	Pineapple	51.39	47.43	3.96 ^{o}C	Decreased
	Carrot	50.95	45.63	10.44	Decreased
Q_a (W)	Ivy gourd	776.66	99.76	28.47	Increased
	Pineapple	704.25	789.38	12.4	Increased
	Carrot	705.64	789.55	11.89	Increased
η_c (%)	Ivy gourd	62.6	77.2	23.4	Increased
	Pineapple	60.72	68.41	12.67	Increased
	Carrot	56.84	68.74	20.94	Increased
η_d (%)	Ivy gourd	6.62	7.8	14.71	Increased
	Pineapple	6.92	7.61	10.01	Increased
	Carrot	7.5	9.55	27.33	Increased
SEC (kWh/kg)	Ivy gourd	1.549	1.144	26.15	Decreased/improved
	Pineapple	4.843	1.573	67.52	Decreased/improved
	Carrot	4.72	3.2	32.2	Decreased/improved
SMER (kg/kWh)	Ivy gourd	0.646	0.875	35.45	Increased
	Pineapple	0.207	0.635	75.85	Increased
	Carrot	0.202	0.302	47.1	Increased

4.3.3. Drying kinetics

4.3.3.1. Moisture content (MC)

The MC of ivy gourd, pineapple, and carrot dried in passive and active setups have been evaluated from the respective mass variation data. The variation of the MC with time for the ivy gourd is displayed in **Fig. 4.9**. As can be observed from **Fig. 4.9**, the MC is decreased slowly for the first two hours of drying because of the huge MC on the surface during initial timings. After 2 h, it started to drop rapidly until it gets a minimum value at 17:00 h (9 h in X-axis time) and the same trend for both passive and active setups on the first days of the experiment. Almost similar trends were observed for pineapple and carrot drying (Figs. are not shown here). The products dried in the active setup have lost more MC as compared to the passive setup in a specific time of drying because higher air velocity carries more MC than the passive setup. Accordingly, ivy gourd reached its final MC of 0.036 kg/kg of db at 19 h in passive setup but it took only 16 h in the active ITSD. It means that the active setup saved 3 h of drying time. Similarly, pineapple was dried to its final MC of 0.417 kg/kg of db in 14 h in the passive, and in 12 h in the active setups. 2 h of drying time was saved in the active setup. Moreover, the MC of the carrot was reduced to 0.448 kg/kg of db after 16 h in passive setup, whereas it took only 13 h in the active setup. Active setup saved 3 h drying time in the active setup. Therefore, active ITSD has performed well in reducing MC as compared to passive setup in all the three cases.

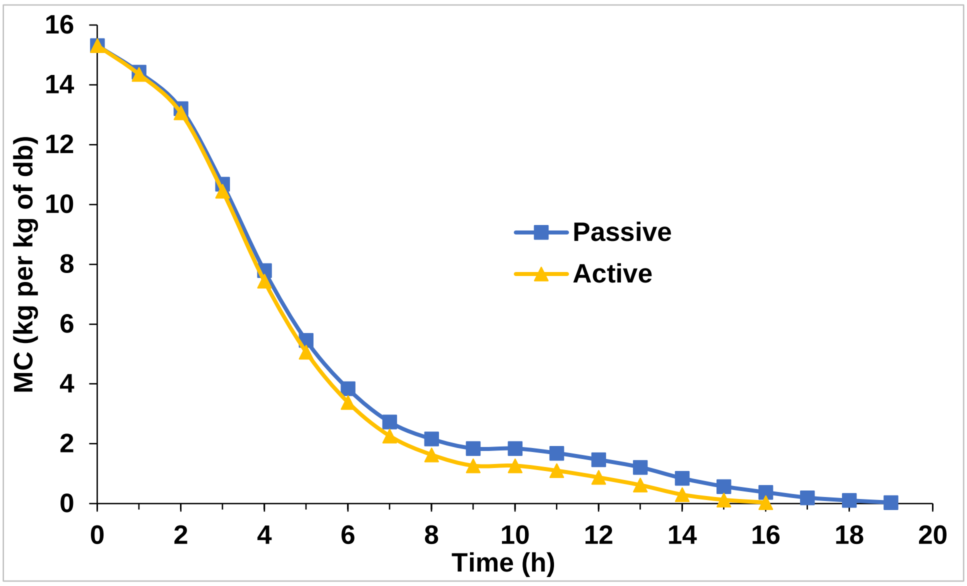


Fig. 4.9. Instantaneous MC of ivy gourd during drying in passive and active ITSDs

4.3.3.2. Drying rate (DR)

The *DRs* of ivy gourd, pineapple, and carrot dried in passive and active ITSDs were estimated and the data of ivy gourd only are described in **Fig. 4.10**. As can be observed from **Fig. 9**, the steep (slope) of the curves increased on the first day with an increasing drying rate until they attain a maximum value at noon (4 h in X-axis time). Then it started to fall at an alarming rate and reached a minimum at 18:00 h. This implies that excess MC on the surface of sample slices could easily be evaporated in the first phase and gradually started to fall as the MC from the surface decreases. Additionally, the drying rates were found to be slow for the second day. It is because the MC is already lost from the outer surface on the first day but removing moisture from the complex inner pores of the sample slices requires much time. So the second day, the drying rate was less. Nearly similar scenes were observed in the pineapple and carrot drying too. The average drying rates for the ivy gourd in the passive and active ITSDs were estimated to be 0.85 and 1.019 kg/h, respectively with a 19.89% improvement for the active setup. The maximum drying rate was 2.37 and 3.01 kg/h for the passive and active setups, respectively, at noon (4 h in X-axis). Similarly, the average DR of pineapple in the passive and actives was 0.375 and 0.447 kg/h, respectively. The maximums for the same were 1.09 and 1.28 kg/h, respectively. Active ITSD showed 19.2% in DR compared to passive setup during drying pineapple. Furthermore, the average DR of carrot in the passive and active setups were 0.502 and 0.561 kg/h, respectively, while active setup revealed an improved of 11.75% compared to the passive setup. And again, the passive setup achieved a maximum of 1.38 kg/h, while the active setup had a maximum DR of 1.74 kg/h at noon. The solutions of the present analysis are in line with the results obtained by Vijayan et al. [117] who dried bitter gourd in an active setup at 2.87 kg/h.

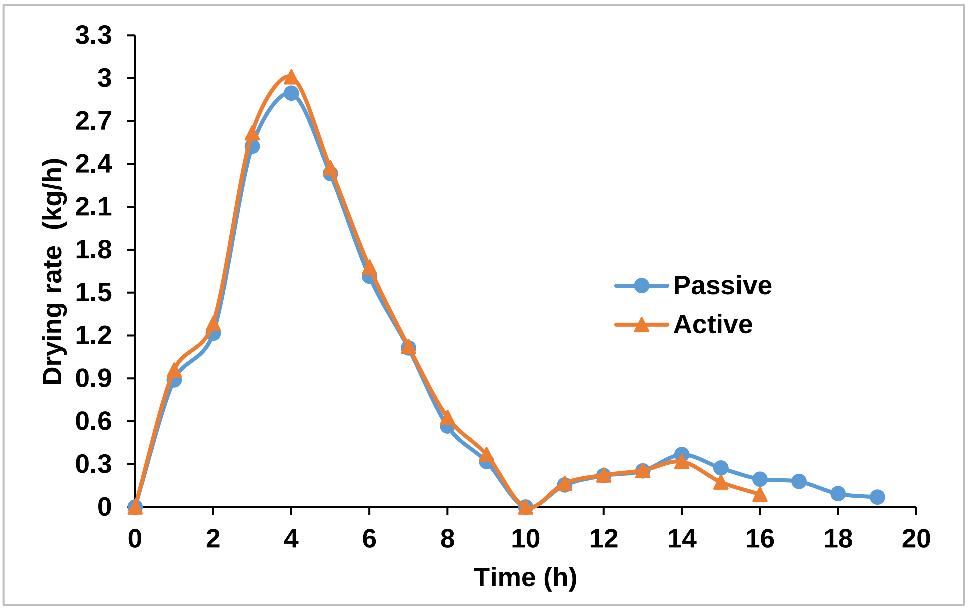


Fig. 4.10. Instantaneous DR of ivy gourd during drying in passive and active ITSDs

4.3.3.3. Moisture ratio (MR)

The instantaneous MR for the samples during drying in both passive and active setups has been evaluated, and the graph of ivy gourd is mentioned in **Fig. 4.11**. The same trend is noticed for the pineapple and carrot slices drying. The MR is in decreasing with respect to time and the results' nature is almost similar to MC versus time which is already explained in **Fig. 4.9**. For both setups, the MR curves of trays 1, 2, 3 and 4 were dropped quickly with the respective order of trays. And again, a faster drop of MR was noticed in the active setup than the passive setup for the respective trays. That is because of fans provided at the inlet of SAC impacted the MR in the active setup. Accordingly, the active setup performed better than passive one in MR during drying of all the three samples drying.

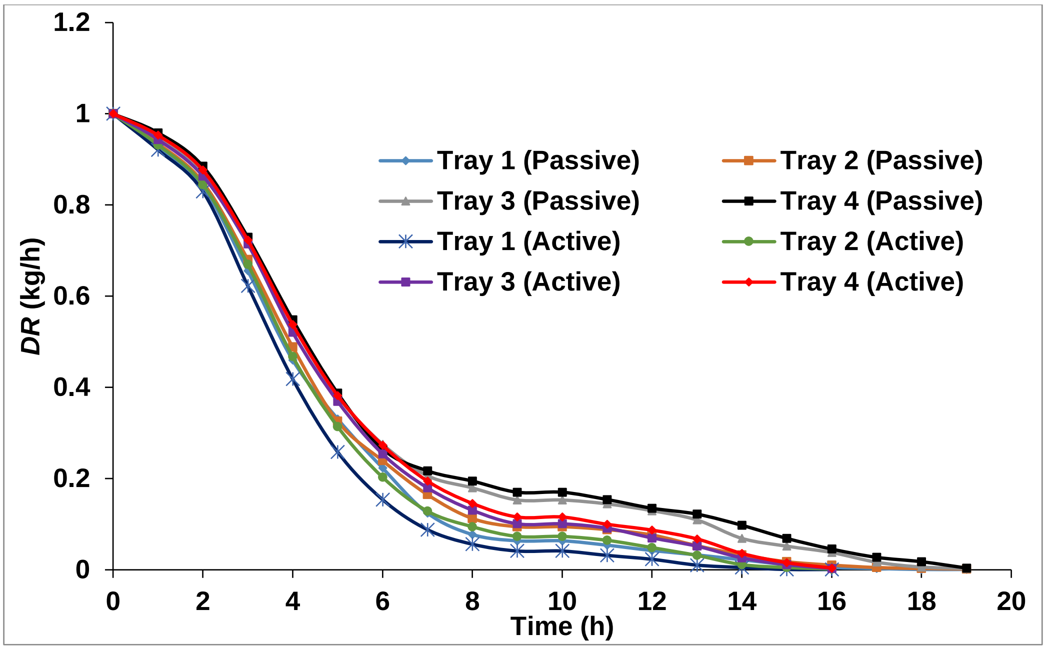


Fig. 4.11. *MR* (db) of ivy gourd during drying in the passive and active ITSDs

4.3.3.4. Moisture diffusion coefficient (D_e)

The D_e of the ivy gourd, pineapple, and carrot have been estimated for both passive and active setups and presented in this section. The instantaneous D_e was plotted for ivy gourd and shown in **Fig. 4.12**. As the drying time increases, the D_e increases continously up to the end of the drying. The D_e for active setup was higher compared to passive setup. It means that in the active setup, the moisture is diffused/transferred more compared to the passive setup because of higher air velocity. The observation was same for all the three samples (Figs. for the pineapple and carrot are not shown here).

Mean values of D_e of ivy gourd in the passive and active setups were 7.06 × 10^{-9} and 8.35 × 10^{-9} m^2/s, respectively. It was in the ranges of 2.286 × 10^{-9} - 1.271 × 10^{-9} m^2/s for the passive setup, and 2.286 × 10^{-9} - 1.935 × 10^{-8} m^2/s for the active setup. The active setup showed an improvement by 19.01 % as compared to passive one. And again, for pineapple, the D_e values were in the range of 2.286 × 10^{-9} - 1.0848 × 10^{-8} m^2/s, while its mean was 7.306 × 10^{-9} m^2/s in the passive setup. For the active setup, the range was from 2.286 × 10^{-9} - 1.264 × 10^{-9} m^2/s, and the mean value was 8.511 × 10^{-9} m^2/s. When compared to passive setup, the active setup demonstrated a 16.5% improvement in D_e of pineapple. Similarly, for carrot slices in the passive and active setups, the mean D_e values were 6.7 and 7.35 × 10^{-9} m^2/s, respectively. The values were in the range of 2.18 × 10^{-9} - 1.08 × 10^{-8} m^2/s for the passive and from 2.29 × 10^{-9} - 1.11 × 10^{-8} m^2/s. There was an improvement of 9.7% in D_e of carrot in active compared to passive setup. The estimated values are better than the existing values from the literature. In the same way, Vijayan et al. [117] gave the range of D_e as 0.863 - 1.368 × 10^{-9} m^2/s. The reported range of values by Tagnamas et al. [120] was 0.8 - 1.368 × 10^{-9} m^2/s which is in good accordance with the results of the current work. Accordingly, active setup performed better than passive setup in D_e for all the three cases.

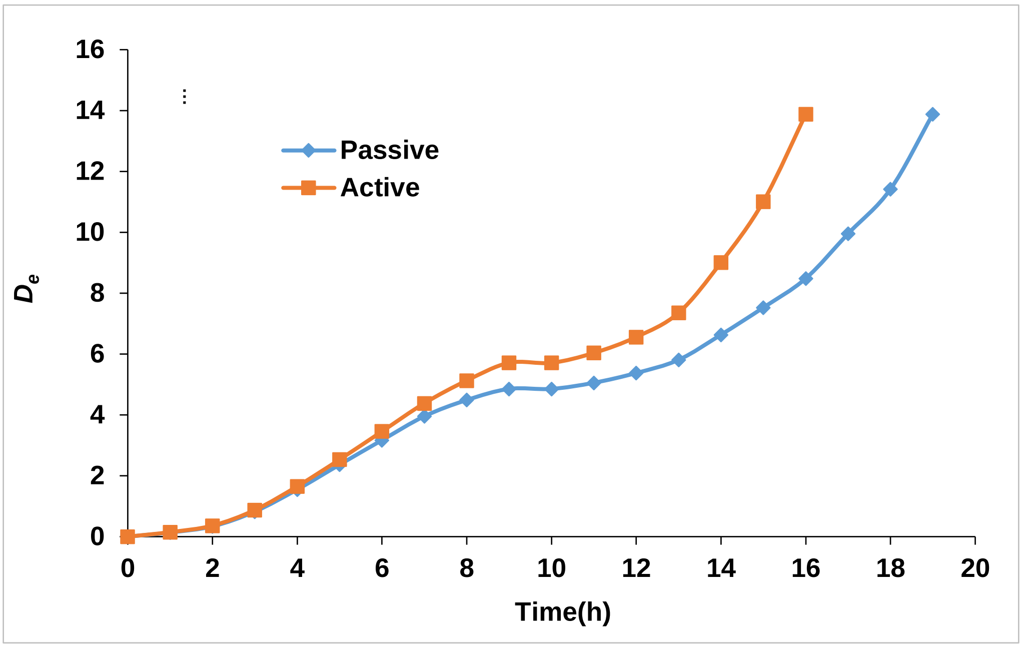


Fig. 4.12. Instantaneous D_e of ivy gourd during drying in the passive and active ITSDs

4.3.3.5. Heat transfer coefficient (h)

The *h* of the ivy gourd, pineapple, and carrot have been calculated for both passive and active setups and discussed in this section. **Fig. 4.13** shows the instantaneous *h* of ivy gourd (pineapple and carrot are not shown). The average *h* for the passive and active ITSD during drying ivy gourd was estimated to be 3.85 and 4.93 W/m^2 K, respectively, which is a 28.05% improvement in the active setup compared to passive setup. Similarly, the average *h* for the passive and active setups during drying pineapple was 9.52 and 12.2 W/m^2 K, respectively, representing a 28.15% enhancement in active setup over passive ITSD. Moreover, for the carrot slices, the average and maximum values of *h* in the passive setup were 6.32 and 12.16 W/m^2K, respectively. And the same for the active setup were 7.25 and 12.66 W/m^2K. Compared to passive setup, active ITSD showed a 14.71% improvement in *h*. The average *h* reported by different authors are; Ekka and Palanisamy [147] (1.6 W/m^2K for red chilli), Goud et al. [105] (5.075 W/m^2K for green chilli) and 3.8 W/m^2K (for okra) which are supporting the results of the current results. Hence, AITSD is better in *h* compared to PITSD.

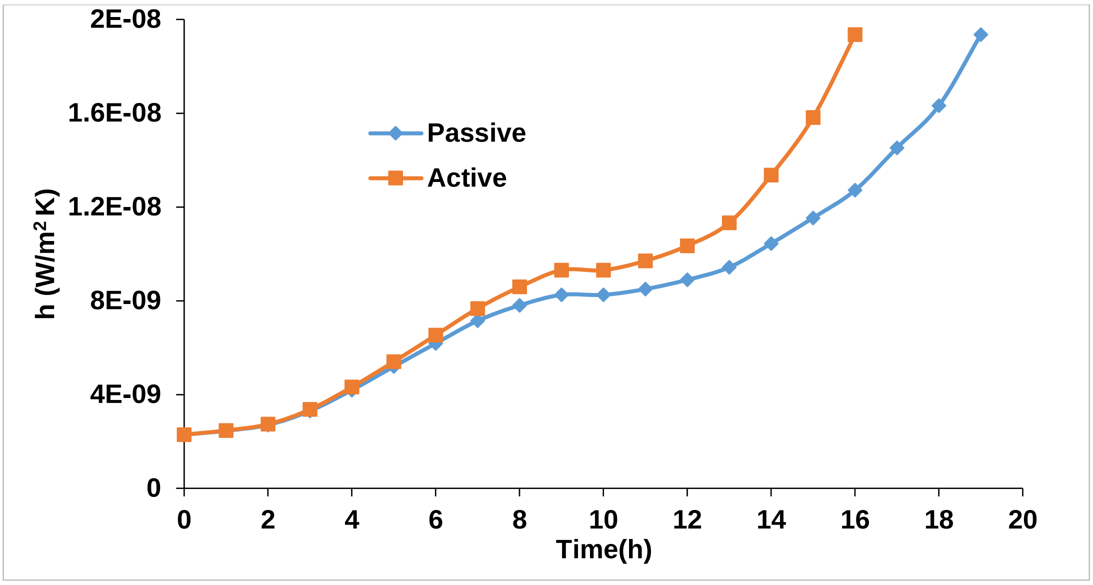


Fig. 4.13. Instantaneous *h* of ivy gourd during drying in the passive and active ITSDs

4.3.3.6. Mass transfer coefficient (h_m)

The variation of h_m with time while drying ivy gourd, pineapple, and carrot slices in passive and active setups has been evaluated and depicted in **Fig. 4.14** (ivy gourd). The h_m is observed to be increasing with time in both setups, but with a higher rate for the active setup. The h_m for ivy gourd was 3.3×10^{-3} and 4.3×10^{-3} m/s in passive and active setups, respectively. It showed that a 30.3% increment of h_m in active ITSD setup. Likewise, for the pineapple drying, the average h_m for the passive and active setups were 0.00825 and 0.0106 m/s, respectively. In the active setup, there was 28.49 % improvement of h_m as compared to passive ITSD. In the same way, for the carrot sliced dried in the passive and active setups, the average h_m was 0.0055 and 0.0065 m/s, respectively; whilst the respective values fell between 0.00041 and 0.011 m/s and 0.00057 and 0.011 m/s. As compared to passive setup, there seemed to be 18.18% more h_m in the active setup. The other reported values were; 0.0033 and 0.0043 m/s [143] and 2.77-3.55 × 10^{-7} m/s [148] and these are in good support of the results of the current study.

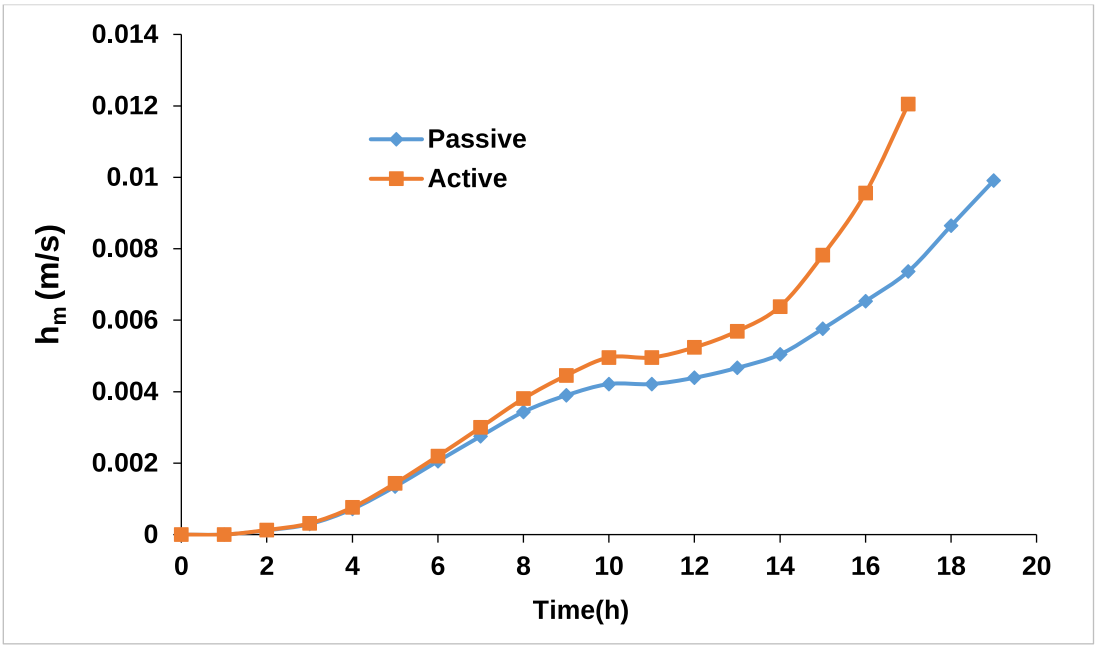


Fig. 4.14. Instantaneous h_m of ivy gourd during drying in the passive and active ITSDs

4.3.3.7. Activation energy (E_a)

The E_a was estimated using the Arrhenius equation from the *MR* data of ivy gourd, pineapple, and carrot slices in passive and active ITSDs. The E_a for the drying of ivy gourd was 39.85 kJ/mol in the passive setup, and 35.54 kJ/mol in the active setup experiments. Similarly, the E_a for the pineapple dried in the passive and active setups were 34.76 kJ/mol and 31.83 kJ/mol, respectively. Moreover, the average values of E_a for the carrot slices were 42.71 and 37.85 kJ/mol for the passive and active setups, respectively. An improvement (decrease) of 8.43-12.84% was observed in the case of active setup compared to passive setup. The obtained values are within the limit of 15–40 kJ/mol for different agricultural food products as reported by Sacilik Kamil [149]. The D_e is negatively correlated with E_a. Due to the enhancement in air velocity, the D_e is higher for active than passive setup which impacts the E_a and hence, E_a is higher for the passive setup. Therefore, the active setup reduced (improved) the E_a compared to passive setup in all the three samples drying experiments.

4.3.3.8. Correlations (D_e, h, and h_m vs. MC)

This section presents the variation of D_e, h, and h_m with MC evaluated for active and passive setups. A characteristic nature of the mentioned parameters (D_e, h, and h_m) with the variation of MC was assessed for all the three samples, and described in **Figs. 4.15** (D_e), **4.16** (h), and **4.17** (h_m) for ivy gourd. The correlation functions, coefficients (R^2) and their constants are mentioned in **Tables 4.2** (ivy gourd), **4.3** (pineapple), and **4.4** (carrot). From the stated Tables, the R^2 values are in between 0.977 and 1. It shows that the developed correlations are a good fit with the estimated parameters and the correlation can be used for future applications without further experimentation.

Table 4.2. Summary of correlation constants of D_e, h, and h_m (ivy gourd)

Parameter (*y*)	***y = a ln (MC) + b***			
	Type of setup	**Correlation constants**		***R²***
		a	***b***	
D_e	Passive	-2×10^{-9}	8×10^{-9}	0.9777
	Active	-3×10^{-9}	1×10^{-8}	1
h	Passive	-1.666	4.9281	0.9777
	Active	-2.292	6.2555	1
h_m	Passive	-0.001	0.0043	0.9777
	Active	-0.002	0.0054	1

Table 4.3. Summary of correlation constants of D_e, h, and h_m (pineapple)

Parameter (y)	***y = a ln (MC) + b***			
	Type of setup	**Correlation constants**		***R²***
		a	**b**	
D_e	Passive	3×10^{-09}	8×10^{-09}	0.9782
	Active	3×10^{-09}	9×10^{-09}	0.9818
h	Passive	-0.004	0.0089	0.9786
	Active	-0.006	0.012	0.9795
h_m	Passive	-4.72	10.234	0.9786
	Active	-6.606	13.88	0.9795

Table 4.4. Summary of correlation constants of D_e, h, and h_m (carrot)

Parameter (*y*)	***y (MC) = a ln (MC) + b***			
	Type of setup	**Constants**		***R²***
		a	***b***	
D_e	Passive	-3×10^{-9}	8×10^{-9}	0.9923
	Active	-3×10^{-9}	9×10^{-9}	0.9904
h	Passive	-4.005	8.5675	0.9922

	Active	-4.203	9.2525	0.9933
h_m	Passive	-0.0004	0.0078	0.9841
	Active	-0.0003	0.007	0.9968

The D_e was plotted with *MC* of ivy gourd and shown in **Fig. 4.15**. As the *MC* decreases, the D_e increases and this increasing trend is in a logarithmic function. The D_e for active setup was higher compared to passive setup. It means that in the active setup, the moisture is diffused/transferred more compared to passive setup because of higher air velocity. Similarly, the variation of h with MC (db) was estimated for both the passive and active setups and is shown in **Fig. 4.16**. The h values are gradually increased when the *MC* decreased from its initial value for both sets of experiments. Similar to $D_{e,}$ the variation of h with the moisture was in a logarithmic trend. Moreover, the variation of h_m with *MC* (db) was illustrated in **Fig. 4.17** and its variation trend is similar to D_e and h. Overall, it is noticed that D_e, h, and h_m varied with MC higher for the active setup as compared to passive setup. The air velocity in the active setup promoted the parameters and hence they are higher in in the active ITSD.

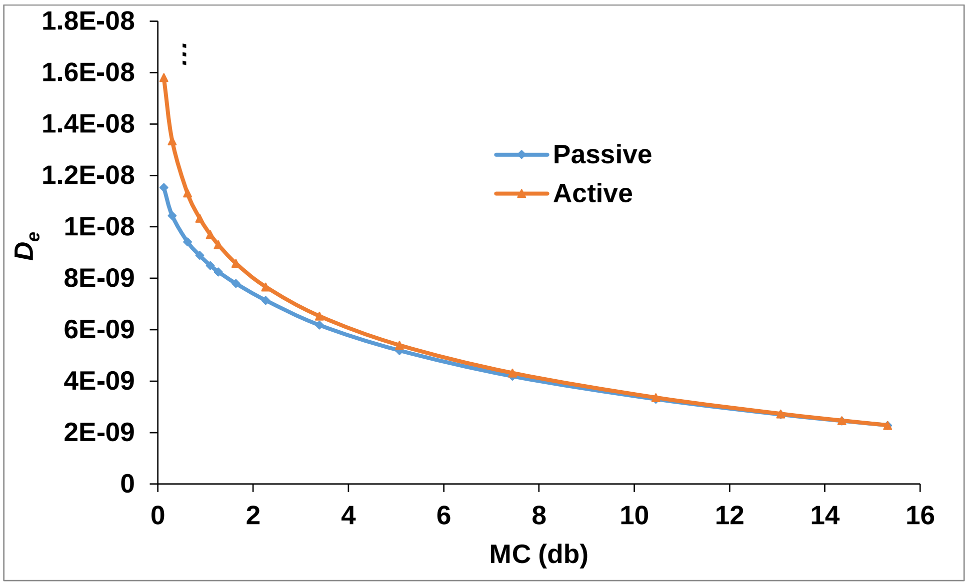


Fig. 4.15. Variation of D_e with MC (db) for the passive and active setups

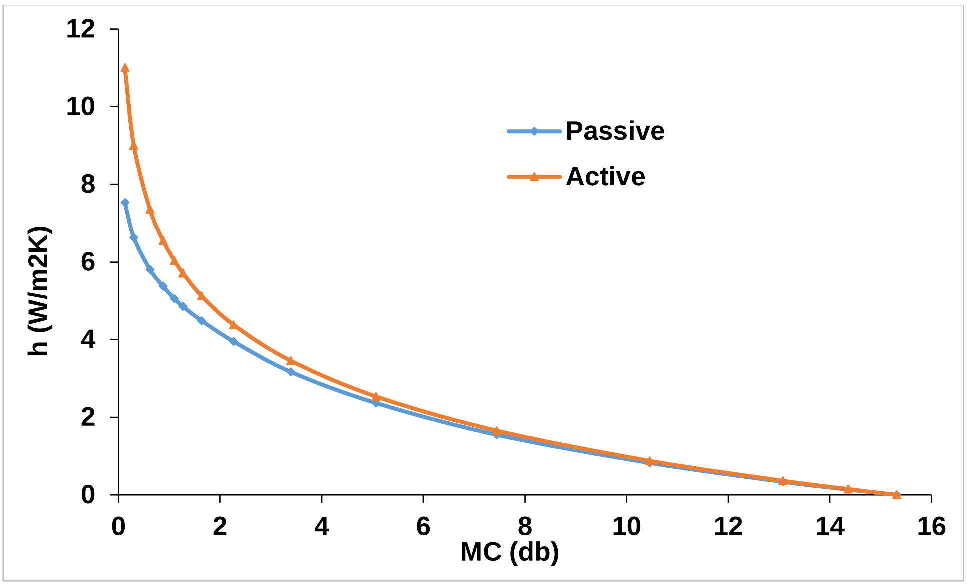


Fig. 4.16. Variation of *h* with MC (db) for the passive and active setups

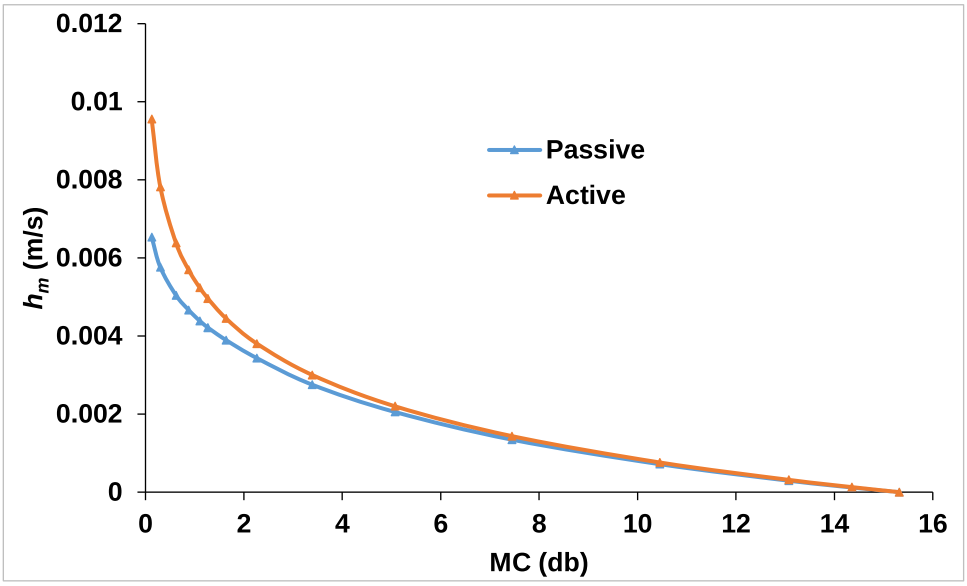


Fig. 4.17. Variation of h_m with MC (db) for the passive and active setups

4.3.3.9. Comparative assessment of the drying kinetics for passive and active ITSDs

In **Table 4.5**, for the passive and active setups, the results of drying kinetics are summarized. Compared to passive setup, the active setup showed improvements for every variable measured/estimated during drying experiments of all the three samples. Accordingly, as stated in **Table 4.5**, the average *DR* was improved by 19.89, 19.2, and 11.75% in the active setup during drying ivy gourd, pineapple, and carrot, respectively. And also, the D_e for drying ivy gourd, pineapple, and carrot was improved by 19.01, 16.5, and 9.7%, respectively. Similarly, the h_m for the same was improved by 30.3, 28.49, and 18.19%, respectively in the active setup compared to the passive setup. In the same way, there was 28.05, 258.15, and 14.72% improvements in h during ivy gourd, pineapple, and carrot drying, respectively. Furthermore, E_a was noticeably improved in the active setup. The D_e, h, and h_m were negatively related in a logarithmic tend with MC. More importantly, the drying time was shortened by 3, 2, and 3 h during drying ivy gourd, pineapple, and carrot, respectively. Hence, based on the results of the drying kinetics, the active ITSD showed a better performance compared to passive ITSD.

Table 4.5. Comparative summary of drying kinetics

Parameter (average)	**Samples**	**Passive**	**Active**	**Variation (%)**	**Remark/ Literature**
DR (kg/h)	Ivy gourd	0.85	1.019	**19.89**	
	Pineapple	0.375	0.447	**19.2**	
	Carrot	0.502	0.561	**11.75**	
D_e (m^2/s)	Ivy gourd	7.06×10^{-9}	8.35×10^{-9}	**19.01**	$0.863–1.37 \times 10^{-9}$ [117]
	Pineapple	7.306×10^{-9}	8.51×10^{-9}	**16.5**	
	Carrot	6.7×10^{-9}	7.35×10^{-9}	**9.7**	
h_m (m/s)	Ivy gourd	3.3×10^{-3}	4.3×10^{-3}	**30.3**	$2.77\text{-}3.55 \times 10^{-7}$ [148]
	Pineapple	8.25×10^{-3}	10.6×10^{-3}	**28.49**	
	Carrot	5.5×10^{-3}	6.5×10^{-3}	**18.18**	
h (W/m^2 K)	Ivy gourd	3.85	4.93	**28.05**	1.63 [147]
	Pineapple	9.52	12.2	**28.15**	
	Carrot	6.35	7.25	**14.72**	
E_a (kJ/mol)	Ivy gourd	36.85	35.54	**10.81**	28.63 [35], 41.46 [95, 142]
	Pineapple	34.76	31.83	**8.19**	
	Carrot	42.71	37.85	**12.84**	
MC (db)		initial	final	-	
	Ivy gourd	15.32	0.144	-	
	Pineapple	7.91	0.417	-	
	Carrot	9.13	0.448	-	
Total time taken to dry (h)	Ivy gourd	16	13	**18.75**	
	Pineapple	14	12	**14.29**	
	Carrot	16	13	**18.75**	

4.4. Indirect type solar dryer (ITSD) supported with TES

In this section, the performance parameters of PITSD and AITSD supported with TES, and the drying kinetics of ivy gourd, pineapple, and carrot dried in both setups are discussed. The two setups are comparatively assessed and presented.

4.4.1. Solar radiation data

During the drying experiments of ivy gourd, pineapple, and carrot, the data of solar radiation was carefully recorded by solar power meter from 8:00 AM to 6:00 PM (in all plots of drying time in X-axis, 0 h means 8:00 AM). The data is presented in **Fig. 4.18** for the drying experiments ivy gourd in PITSD and AITSD integrated with a system containing PCM as a TES. The maximum value was recorded to be 962 W/m^2, the minimum record was 184 W/m^2 and its average value was 662 W/m^2 in PITSD while the same was 967, 181, 663.1 W/m^2, respectively, in AITSD. Similarly, for the drying dates of pineapple, its maximum value was 961 W/m^2, minimum value was 181 W/m^2, and average was 615 W/m^2 in the PITSD, while the same for the AITSD, 978, 185, 622 kW/m^2, respectively. Moreover, on the drying experiment dates of carrot, the maximum value in the passive was 972 W/m^2, the minimum value being 173 W/m^2, and the average was 623.26 W/m^2. Whereas, in the active setup, the maximum, minimum, and average values were 955, 182, and 611.46 W/m^2, respectively. The recorded data of solar radiation seems to be equivalent for all the respective experiments dates of passive and active setups so that no significant difference would be on the results of the two setups due to solar radiation variation.

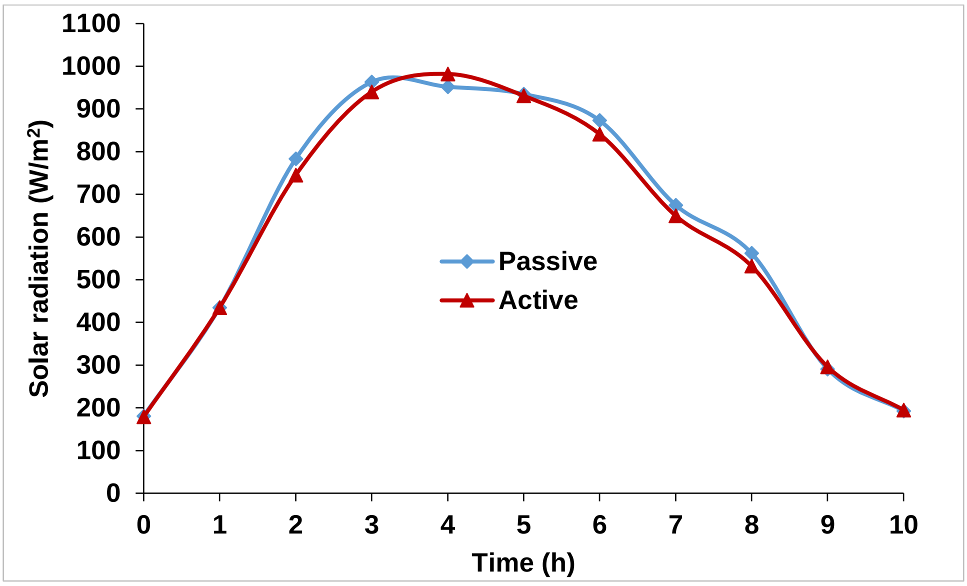


Fig. 4.18. Solar radiation for ivy gourd drying dates PITSD and AITSD supported with TES

4.4.2. Performance parameters

4.4.2.1. Temperature distribution

The data of temperature distribution of ivy gourd, pineapple, and carrot in PITSD and AITSD supported with TES were recorded and depicted in **Figs. 4.19 (a)** and **(b)** (ivy gourd), respectively. The experiments (for all sample) were performed from morning 8:00 AM to midnight (12 o' clock) for both setups. The temperature data was recorded hourly during the drying duration. The temperatures of ambient air, collector inlet, outlet, 1st, 2nd, 3rd and 4th trays are represented by T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3, and T_4, respectively, for the convenience of this discussion.

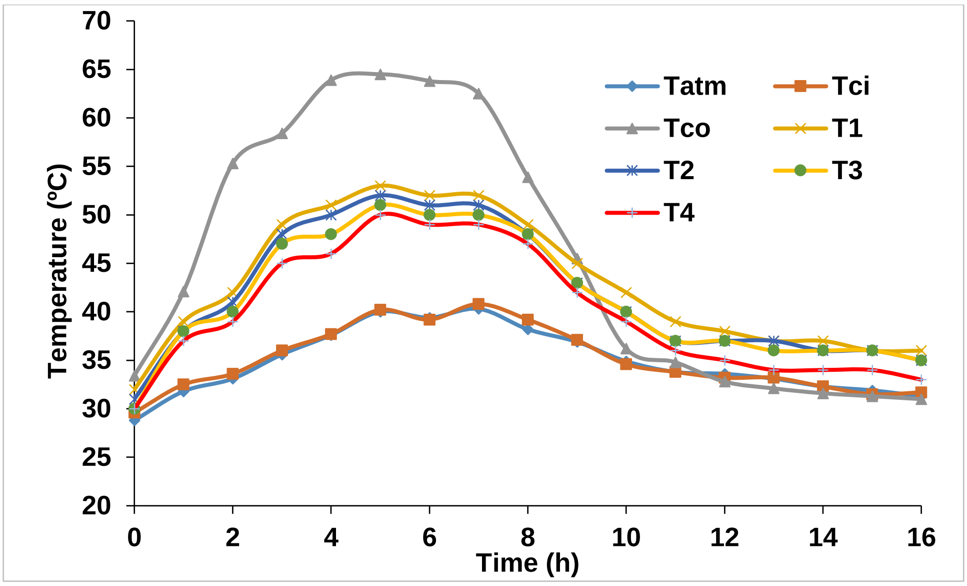
The temperature distribution of PITSD during drying ivy gourd is presented in **Figs. 4.19 (a)**. The maximum T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3, and T_4 were noticed to be 40.3, 40.5, 64.5, 53, 52, 51, and 50 °C, respectively. The minimum of the same was observed to be 28.8, 29.6, 31, 32, 31, 30, and 30 °C, respectively; while the averages were 34.9, 35.1, 45.5, 42.9, 41.8, 41.3, and 39.9 °C, respectively. **Figs. 4.19 (b)** depicts the temperature distribution in the AITSD during drying ivy gourd. The maximum values of T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3, and T_4 were observed at 41.2, 44.8, 61, 54, 52, 50, 47 °C, respectively. And their minimum was 28.8, 29.8, 28, 31, 31, 31, and 30 °C, respectively. Whereas the average values of the same were evaluated to be 35, 36.9, 42.6, 42.1, 40.8, 40.4, and 39.2 °C, respectively.

Similarly, the distribution of temperature inside the PITSD during drying pineapple have been recorded. Accordingly, 40.2, 40.2, 66.5, 56, 55, 54, and 54 °C were the maximum values for T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3, and T_4, respectively. And 26.4, 26.8, 28, 31, 30, 30, and 29 °C were minimum values for the same, respectively; while their respective averages were 33.2, 33.4, 44.9, 44.5, 43, 41.3, and 42.4 °C. Similarly, during the drying of pineapple in the AITSD, the T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3, and T_4 were maximum at 40, 43.5, 63, 55, 54, 54, 53 °C, respectively. Their minimum temperatures were 29, 30.1, 29, 34, 34, 33, and 33°C, respectively. And their respective average values were 34.9, 36.2, 43.4, 43.8, 42.6, 42.1, and 40.7 °C.

Moreover, the temperature distribution during drying carrot in the PITSD, 38.2, 41, 71, 52, 51, 51, and 51 °C were observed as maximal T_a, T_i, T_o, T_1, T_2, T_3, and T_4, respectively. And the lowest temperatures to be observed were 28.5, 28, 27.5, 30, 29, 29, and 29 °C, respectively. The mean temperatures to be observed were 33.6, 34.2, 45.7, 41.1, 40.5, 40, and 39.1 °C, respectively. Similarly, during the drying process of carrots in the AITSD, the maximum values for T_{atm}, T_{ci}, T_{co}, T_1, T_2, T_3 and T_4 were detected as 40.5, 42, 70, 50, 49, 47, and 46 °C, respectively. Their minimum temperatures were 29, 28, 27.5, 31, 30, 30, and 29 °C and the averages were 34.3, 35.1, 44.3, 40.1, 39.7, 38.5, and 37.5 °C, respectively.

Generally, as implied in **Figs. 4.19 (a)** and **(b)**, the curves of temperature distributions in both setups seem to be similarly behaved. For both setups, the TES system absorbed heat in the sunshine hours and released it after the sunset maintaining a nearly constant temperature for about 6 hours even if T_{atm}, T_{ci}, and T_{co} were observed to be decreasing. But still, variation between PITSD and AITSD is noticed that higher temperature values in PITSD than AITSD. This could be because of the high air velocity in the case of AITSD, which promoted faster heat and mass transfer.

(a)



(b)

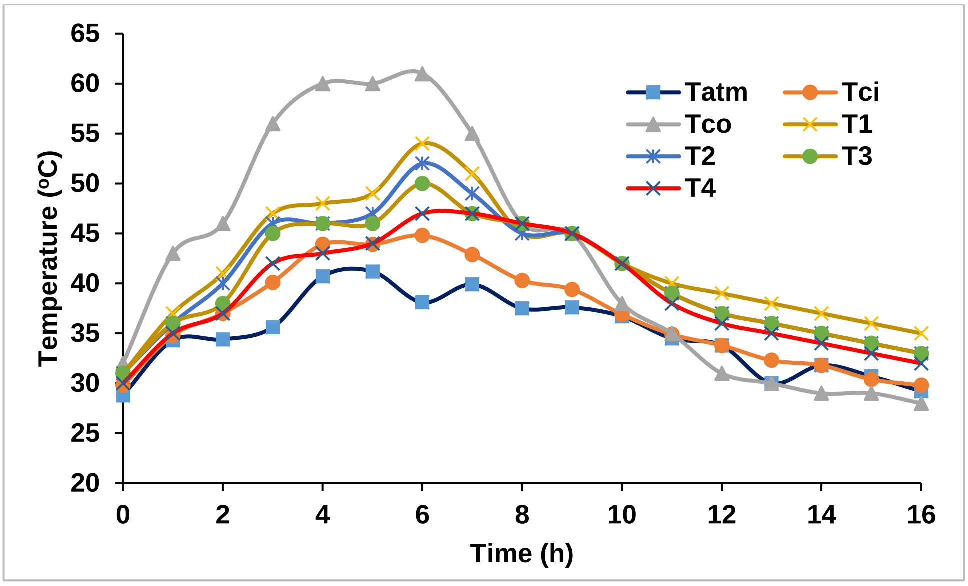


Fig. 4.19. Variation of temperature distribution with time in setup (a) PITSD and (b) AITSD

4.4.2.2. Actual heat supply (Q_a)

The Q_a in PITSD and AITSD during drying ivy gourd, pineapple, and carrot has been estimated and described in **Fig. 4.20** (shown for ivy gourd only). For ivy gourd drying, the average Q_a was evaluated to be 735.9 and 761.2 W for the setups PITSD and AITSD, respectively. Its maximum was 1184.9 W for PITSD and 1253 W for AITSD. Similarly, for the pineapple drying, the average Q_a was determined to be 813 and 902 W, for the PITSD and AITSD configurations, respectively. Moreover, the mean values of Q_a for the PITSD and AITSD were determined to be 722 and 807.4 W, respectively, while the maximums for the same were 1218.6 W and 1444.7 W.

It shows that the Q_a of the AITSD was higher than that of the PITSD because, in the case of AISD, the enhanced mass flow rate has a direct impact on Q_a which states that heat supply is proportional to mass flow rate and temperature change [108]. And hence, AITSD with TES performed well in Q_a compared to PITSD with TES during drying all the three samples.

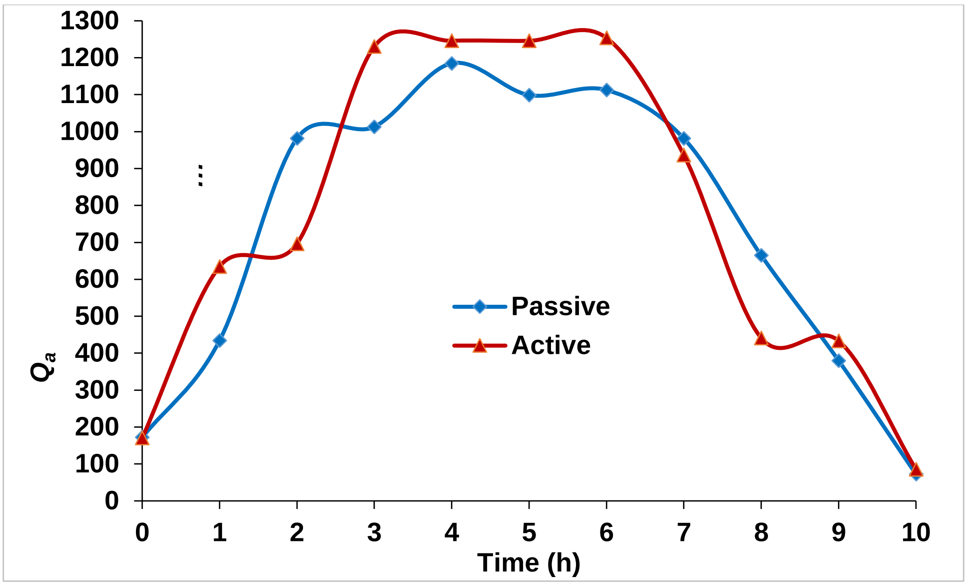


Fig. 4.20. The variation of Q_a during drying ivy gourd in PITSD and AITSD with TES

4.4.2.3. Collector efficiency (η_c)

The η_c of PITSD and AITSD is evaluated from the solar radiation data recorded during drying ivy gourd, pineapple, and carrot. Its variation with time is represented in **Fig. 4.21** for the data of ivy gourd drying. The average, minimum, and maximum η_c of drying ivy gourd in PITSD was estimated to be 66.7, 52.7, and 80.8%, respectively. The same was 69.3, 46.1, and 82.8%, respectively, in AITSD. The average η_c for AITSD was 4.75% higher than that of setup PITSD. Similarly, for the pineapple dried in PITSD, the average, minimum, and maximum η_c was calculated to be 58.18, 9.8, and 89.7%, respectively. In AITSD, the same were 67.79, 16.02, and 93.00%, respectively. In drying pineapple, the average η_c for AITSD showed a 16.52% improvement compared to the PITSD setup. Moreover, during drying carrot, the minimum, average and maximum η_c for PITSD and AITD have been evaluated to be 31.9 and 36.2%, 59.7 and 67.8%, and 75.9 and 82.7%, respectively. And the average improvement of η_c was 13.6% in the AITSD compared to PITSD during drying carrot. Mugi and Chandramohan [77] reported 63% of η_c in a AITSD, and Amjad et al. [79] found 50-60% of η_c in AITSD that is in a good agreement with the average values of the current study.

Generally, the rate of mass flow and temperature variation directly influence the amount of heat that is supplied. For both configurations, the maximum value of η_c was observed at midday as the η_c is related to solar intensity and irradiance is high at noon [144]. Accordingy, AITSD performed better than PITSD in supplying actual heat. The reason for this is that increased air velocity (greater mass flow rate) improved the Q_a, which has an impact on η_c.

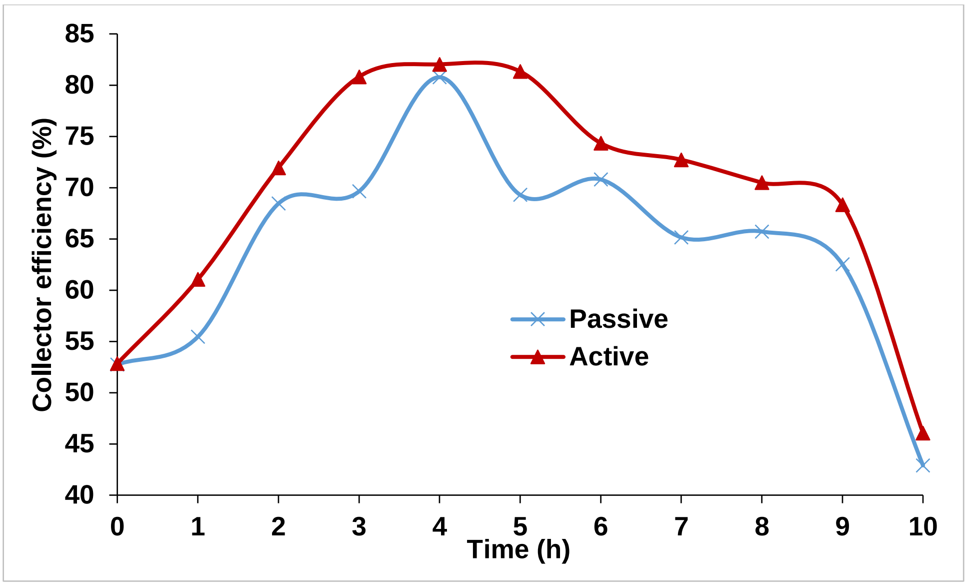


Fig. 4.21. The variation of the η_c during drying ivy gourd in PITSD and AITSD with TES

4.4.2.4. Drying efficiency (η_d)

The η_d of passive and active ITSDs has been evaluated from the data recorded by drying ivy gourd, pineapple, and carrot. And its variation with time for the pineapple drying is displayed in **Fig. 4.22**. The amount of moisture available in a drying object is directly related to input energy [150, 151]. From **Fig. 4.22**, the η_d was observed to be increasing with time for the first instants of time until the maximum value was attained. The average η_d for PITSD and AITSD assessed to be 13.5 and 15.2%, respectively. AITSD showed 11.3% improvement as compared to PITSD. Similarly, for the pineapple drying, the mean values of η_d for PITSD and AITSD, respectively, were 9.7 and 11.9%. When compared to PITSD, AITSD exhibited a 22.7% improvement in η_d. Moreover, based on the assessment of carrot drying, PITSD and AITSD setups experienced an average η_d of 11.1 and 14.2%, respectively. There were 27.93% improvements in the AITSD compared to PITSD. Accordingly, the result are in good agreement with the existing literature by Muthukumar et al. [151] (10.8%); by Tagnamas et al. [32] (2.6 – 4.2%) during drying carob seeds in a forced ITSD; and by Bhardwaj et al. [68] (10.53%) in an ITSD supported with TES during drying medicinal herbs. Thus, from these results, AITSD TES showed better drying efficiency than PITSD TES.

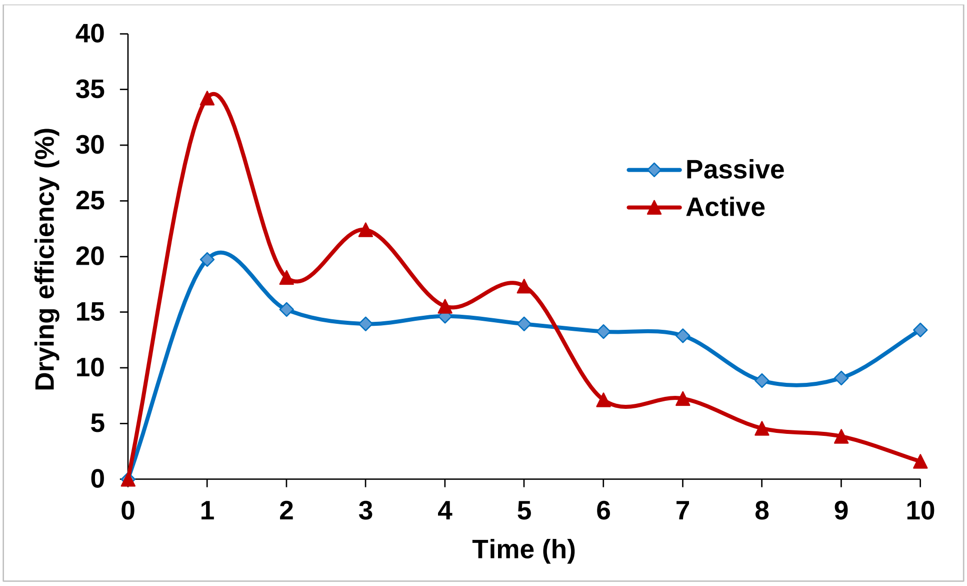


Fig. 4.22. Variation of the η_d during drying ivy gourd in PITSD and AITSD with TES

4.4.2.5. Specific energy consumption (SEC)

The SEC was assessed using Eq. (10) for drying of ivy gourd, pineapple, and carrot in PITSD and AITSD supported with TES. Accordingly, its values were evaluated to be 0.265 and 0.228 kWh/kg for PITSD and AITSD, respectively for the ivy gourd drying. It means that there was 13.96% more consumption of energy per kg of the sample slice in PITSD compared to AITSD.

Similarly, for pineapple drying, the SEC was estimated to be 322 and 273 Wh/kg in PITSD and AITSD, respectively. There was a 15% SEC improvement in drying pineapple in AITSD compared to PITSD. The results of the current study are in good agreement with the results reported in the existing literature [63].

Moreover, the SEC of PITSD and AITSD supported with TES during drying carrot was 0.276 and 0.219 kWh/kg, respectively. In the passive setup, the sample consumed 20.7% more energy per kg than in the active one. Compared to previously reported values [26, 39], it is a relatively better achievement. Hence, the PITSD consumed more energy than the AITSD.

4.4.2.6. Specific moisture extraction rate (SMER)

The SMER was evaluated using Eq. (11) for the drying data of ivy gourd, pineapple, and carrot in PITSD and AITSD supported with TES. It is 3.78 and 4.38 kg/kWh for PITSD and AITSD, respectively. It means that the AITSD removed 0.6 kg/kWh more moisture per kWh of energy than setup PITSD which is an improvement of 15.87%. It is in line with the reported values in the existing literature [60, 143].

Similarly, during drying pineapple, the SMER was estimated to be 3.10 and 3.67 kg/kWh for PISD and AISD, respectively. There was an 18.39% SMER improvement in drying in AITSD compared to PITSD. The results of the current study are in good agreement with the results reported in the existing literature [63].

Moreover, the SMER evaluated for PITSD and AITSD was 3.6 and 4.6 kg/kWh, respectively. The results show that the AITSD removed 1 kg/kWh greater moisture/kWh of energy than the PITSD setup showing a 27.8% improvement. Compared to previously reported values [26, 39], it is a relatively better achievement. Comparatively, AITSD showed better result in SMER.

4.4.3. Drying kinetics

4.4.3.1. Moisture content (MC)

The MC was evaluated from the recorded data of mass variation during drying the sample slices of ivy gourd, pineapple, and carrot in both passive and active setups of ITSD integrated with TES. **Fig. 4.23** shows the variation of MC of ivy gourd with time. The MC dropped faster for AITSD than that of PITSD, which is due to the influence of mass flow rate promoted by CPU fans for AITSD. The curves of both setups fall rapidly before 1:00 PM and start to decrease slowly up to the final point (midnight 12 o'clock). It was because of the abundant availability of MC on the surface of sample slices that contributed to the curves dropping rapidly in the first instant of drying. The MC of the ivy gourd was reduced from 15.56 to 0.184 (db) within 16 and 14 h in PITSD and AITSD, respectively. Similarly, it took 16 and 14 h to reduce the MC of pineapple from 7.9 to 0.417 (db), respectively. And the carrot sliced dried from 1.93 to 0.478 (db) in 15 and 12 h, respectively. The result of the current work is in good agreement with the report by Mugi and Chandramohan [152] who dried guava slices from 5.5355 - 0.0244 (db) in 18 and 14 h in AISD and PISD without TESS, respectively.

In general, relatively AITSD showed better performance as compared to PITSD while removing the MC. The presence of the TES helped the drying to run continuously without interruption so that it minimized the microbial growth on the semidried sample that could happened on without TES case. Moreover, after sunset, the TES unit enhanced the drying process for 6 extra hours because both setups produced an average temperature difference of 5.3 ºC for PITSD and 3.74 ºC for AITSD after 6.00 PM.

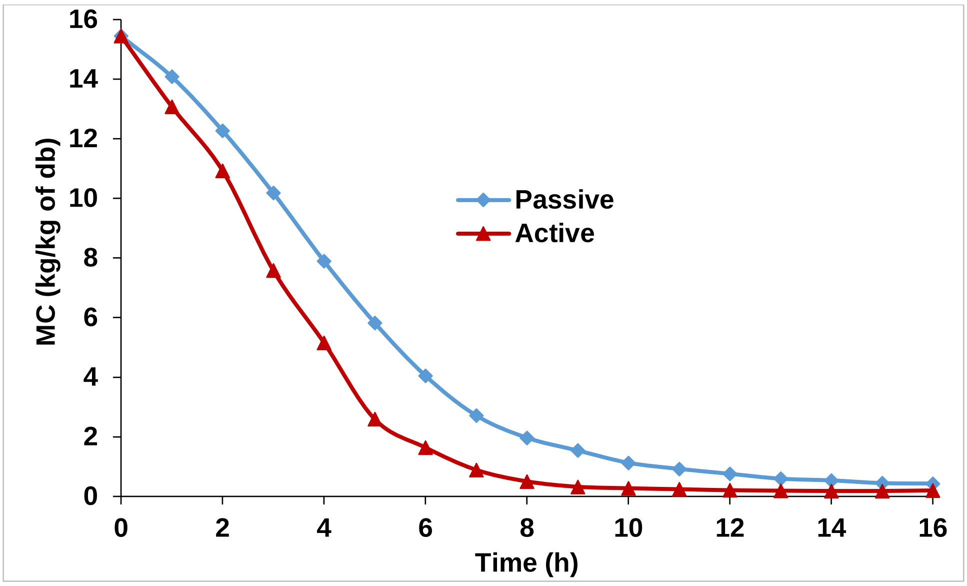


Fig. 4.23. Variation of the *MC* during drying ivy gourd in PITSD and AITSD with TES

4.4.3.2. Drying rate (DR)

The variation of *DR* with time is characteristically represented in **Fig. 4.24** (ivy gourd). As implied in **Fig. 4.24**, the drying rate increased with increasing rate until it attained a maximum point at noon. After the maximum point, it is seen to fall with increasing time for both setups. The excess moisture on the surface of the sample in the initial stage of the drying favored the drying rate to increase at a fast rate. After the maximum point, moisture available inside the complex inner pores needs much time and energy to be removed [143]. The maximum drying rates of ivy gourd in PITSD and AITSD at noon (4 h at X-axis) were 2.28 and 3.35 kg/h, respectively. And also, for the pineapple, the average DR in PITSD and AITSD was 0.408 and 0.45 kg/h, respectively, indicating a 10.3% improvement in AITSD. At noon, the PITSD and AITSD had peak DRs of 1.02 and 1.17 kg/h, respectively. Similarly, an average drying rate of 0.49 kg/h was observed for drying carrot in PITSD and 0.53 kg/h for AITSD while the corresponding maximum was 1.23 kg/h in the passive and 2.198 kg/h in the active setups.

Comparatively the *DR* of the samples in AITSD was faster than that of PITSD. Even though the experiment was completed within a day with the support of TES, it took 2-3 extra hours to dry the sample slices in PITSD compared to AITSD which is the effect of air velocity incurred for setup. The overall result is matched with the result report by Lamidi et al. [71].

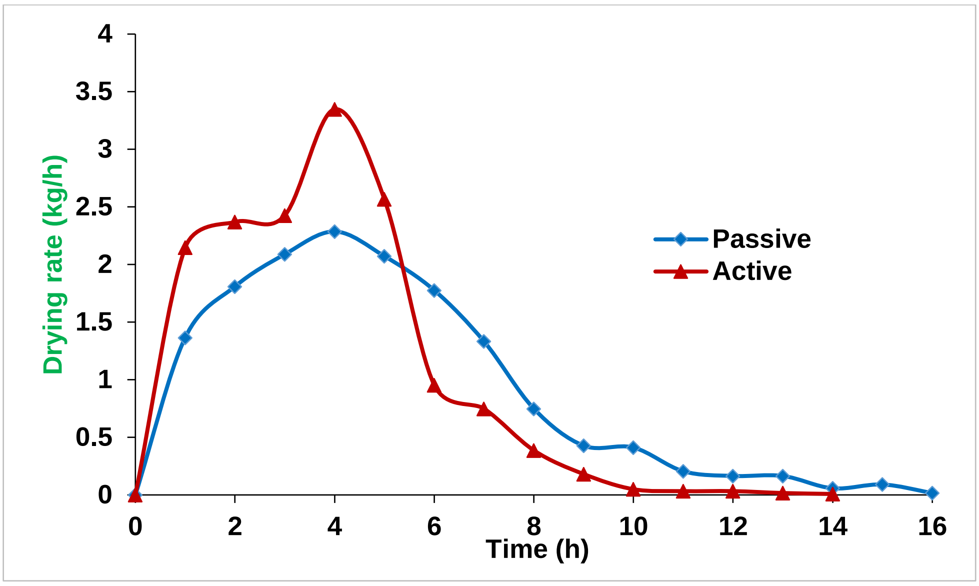


Fig. 4.24. Instantaneous *DR* of ivy gourd dried in PITSD and AITSD with TES

4.4.3.3. Moisture diffusion coefficient (D_e)

The D_e have been assessed from the experimental data obtained during drying ivy gourd, pineapple, and carrot. Its variation with time is described in **Fig. 4.25** (ivy gourd as sample). The D_e ascended with time from the beginning to the end of the experiment. After midday, the D_e of AITSD is raised with a higher rate than that of PITSD up to the sunset and started to increase with a decrease after the sunset (or at the final stage). The D_e in PITSD continued to increase with a slight constant rate up to the final point. The influence of mass flow rate is believed to be responsible for such differences.

The average value of D_e for ivy gourd drying is estimated to be 8.0604×10^{-09} and 10.00025×10^{-09} m^2/s for PITSD and AITSD, respectively. AITSD showed 24.13% improvement in D_e as compared to PITSD. Similarly, the D_e for drying pineapple in the PITSD and AITSD was in the range of $2.286 - 9 \times 10^{-09}$ and $2.39 - 9.96 \times 10^{-09}$ m^2/s, and the average values of D_e for the same were 5.23×10^{-09} and 5.97×10^{-09} m^2/s, respectively. AITSD showed better performance (a 12.4% improvement) in D_e compared to PITSD. And also, for the carrot drying, it has been estimated that the average D_e was 7.2×10^{-09} and 8.3×10^{-09} m^2/s for the PITSD and AITSD, respectively. The D_e gave a 16.9% improvement in AITSD compared to the PITSD. Results in the literature provided by Reyes et al. [144] while drying mushrooms in a TES aided hybrid solar dryer were $2.5 - 8.4 \times 10^{-10}$ m^2/s which indicates that results in the current study are comparable. Hence, the AITSD supported with TES improved D_e compared to PITSD.

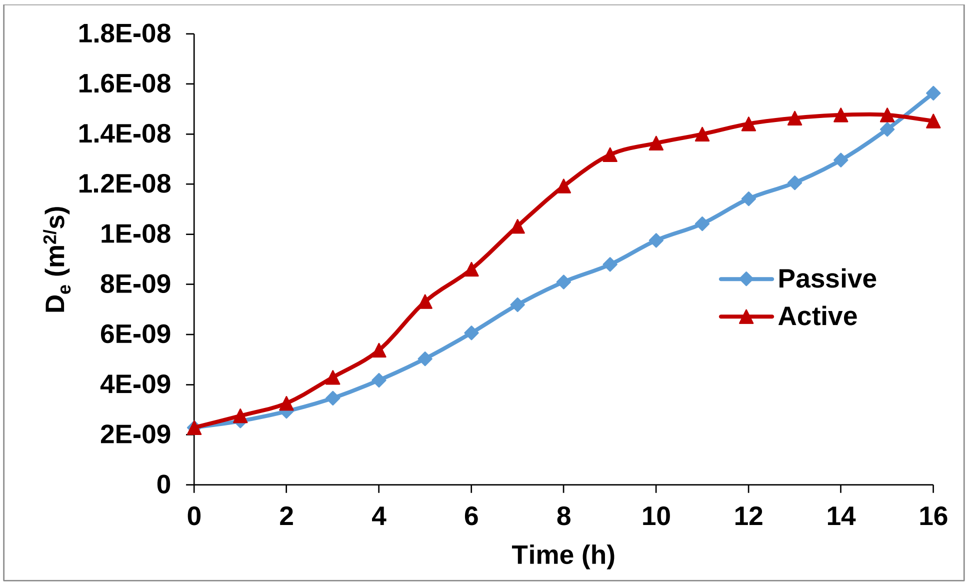


Fig. 4.25. Variation of D_e with time for ivy gourd in PITSD and AITSD supported with TES

4.4.3.4. Heat diffusion coefficient (h)

Figure 4.26 depicts the characteristic trend of heat transfer coefficient (*h*) with time (**ivy gourd**). It has been evaluated from the experimental data of drying ivy gourd, pineapple, and carrot using Eq. (18). As can be noticed from **Fig. 4.26**, the trend of variation in *h* is similar to the trend noticed in D_e (**Fig. 4.25**). The *h* increased with an increasing rate for the sunshine hours and at the final stage, there is a slight decrease because of temperature drop after the sunset in AITSD. Unlike the curve of AITSD, the PITSD ascended with a constant rate from beginning to end.

The average values of *h* for PITSD and AITSD were estimated to be 4.7 and 6.28 W/m^{2}K, respectively. The AITSD performed an improvement of 1.85 W/m^2 K (33.62%) as compared to PITSD. Additionally, for the pineapple drying, the mean values of *h* for PITSD and AITSD were estimated to be 5.63 and 6.47 W/m^{2}K, respectively. AISD showed an improvement of 14.92% compared to PITSD. Similarly, during drying carrot, the PITSD and AITSD were found to have average *h* values of 7.1 and 8.3 W/m^2 K, respectively with a 1.2 W/m^2 K difference between them indicating that the latter has achieved a 16.9% improvement. The *h* values obtained in the existing literature of Tiwari [153] (0.69-14.45 W/m^2 K) are almost similar to the present value. Accordingly, AITSD was better in *h* compared to PITSD.

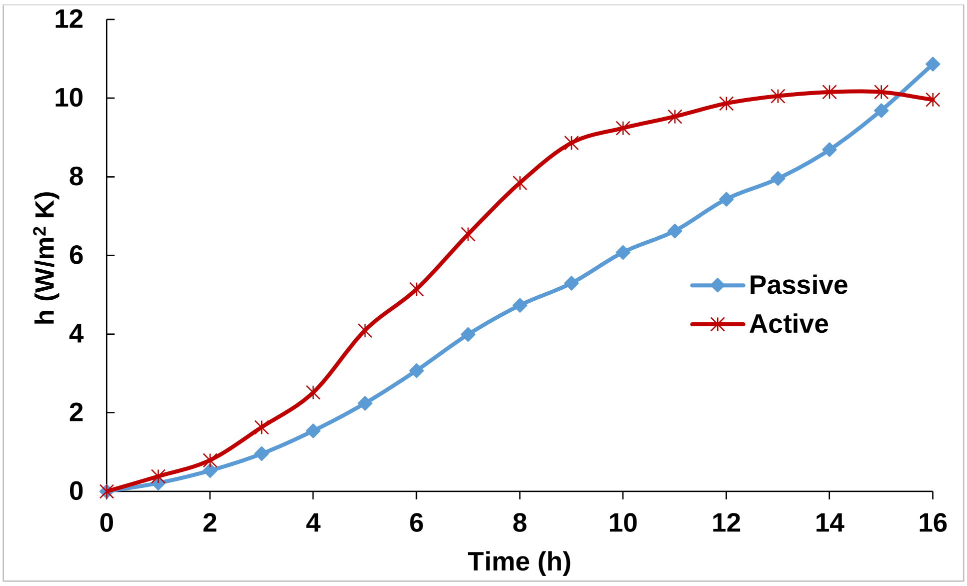


Fig. 4.26. Variation of *h* with time for ivy gourd in PITSD and AITSD supported with TES

4.4.3.5. Mass diffusion coefficient (h_m)

Equation (18) is employed to assess the h_m for the experimental data of ivy gourd, pineapple, and carrot dried in passive and active setups with TES. The trend of variation with time for the **ivy gourd** is sketched and displayed in **Fig. 4.27**. From the **Fig. 4.27**, the characteristic trend of the graph of h_m was observed to behave similarly to the trends of that of D_e and *h* of the current study.

For the ivy gourd slices, the average values of h_m were estimated to be 0.0041 and 0.0055 m/s for setup PITSD and AITSD, respectively. The difference observed is 0.0014 m/s implying that 34.15% improvement is achieved by AITSD in comparison with PITSD. Similarly, the average values of h_m for pineapple in PITSD and AITSD were 0.00489 and 0.00576 m/s, respectively. The AITSD showed an 8.81% improvement of h_m over PITSD. Moreover, for the carrot slices dried in the PITSD and AITSD, h_m was calculated to be 0.0062 and 0.0071 m/s, respectively. In comparison to PITSD, AITSD showed an improvement of 14.52%. The estimated values of h_m are with good coincides with the existing values reported in Ghanbarian et al. [148] (2.77-3.55 × 10^{-7}) during drying Bisporus mushroom; and its values are also very close to the existing values mentioned by Goud et al. [105] during drying green chilli (0.00441 and 0.00297 m/s) and okra (0.0033 and 0.00257 m/s) in passive and active ISDs, respectively. Accordingly, AITSD improved the h_m during drying the samples compared to PITSD.

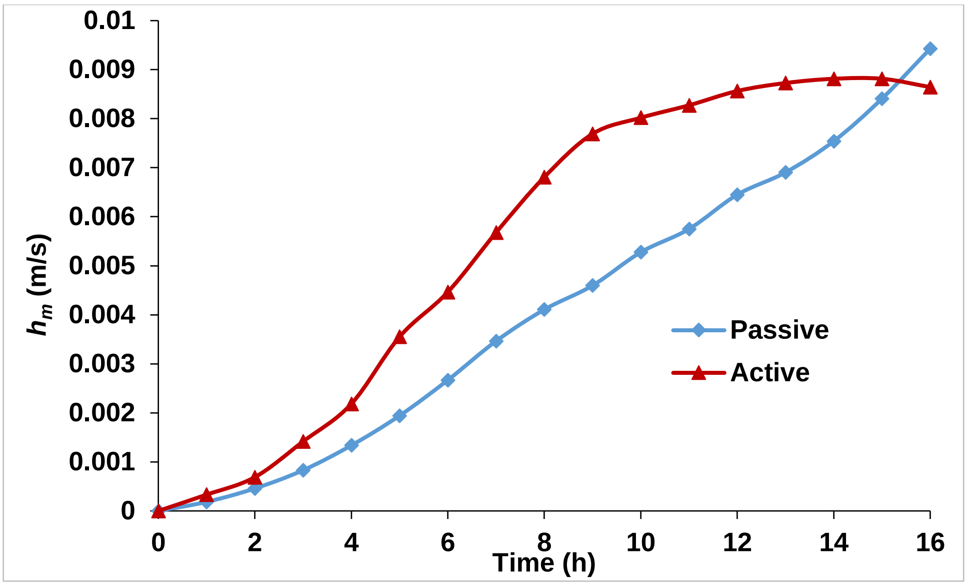


Fig. 4.27. Variation of h_m with time for ivy gourd in PITSD and AITSD supported with TES

4.4.3.6. Activation energy (E_a)

During drying ivy gourd, pineapple, and carrot, the E_a has been evaluated for both PITSD and AITSD. Accordingly, the estimated E_a values for the ivy gourd were found to be 39.35 and 36.35 kJ/mol for PITSD and AITSD, respectively. Consequenrtyly, the AITSD performed better by showing a 7.63% improvement in E_a compared to PITSD. Similarly, for pineapple, the average value of E_a was 42.72 and 38.35 kJ/mol for PITSD and AITSD, respectively. There was an 8.1% improvement in E_a in AITSD compared to PITSD. Also, the carrot dried in the PITSD and AITSD had an E_a of 45.1 and 39.6 kJ/mol, respectively. As the result, the AITSD improved the E_a by 12.2% over PITSD. While drying agriproducts in a solar dryer, Sacilik [149] found similar results (15–40 kJ/mol). Therefore, PITSD required more E_a than the AITSD supported with TES in drying the samples.

4.4.3.7. Correlations (D_e, h, and h_m vs. MC)

Correlations between MC (db), D_e, h_m and h have been assessed from experimental data recorded during drying ivy gourd. The trends of the variations were traced and mathematically related. All the three variables namely D_e, h_m and h found to vary with the relation $y = a\ ln(MC) + b$, where a and b are correlation constants, MC represents the independent variable MC (db), $y(MC)$ stands for the dependent variables (D_e, h_m or h) and R^2 is correlation coefficient. The constants are evaluated from the correlation function and are described in **Tables 4.6** for ivy gourd, pineapple, and carrot. As indicated in the Table, R^2 was in between 0.9756 to 1 for D_e, h_m and h of PITSD and AITSD, indicating a strong correlation between MC and the variables.

The correlation between D_e and dry base MC has been examined from the experimental data drying ivy gourd, pineapple, and carrot in both setups, and described **Fig. 4.28** (ivy gourd data is shown as a sample). The trend was similar for all the three sample data, but the graph for the pineapple and carrot are not shown here. The D_e shows a negative correlation with the MC in a logarithmic trend. As the MC decreases, the D_e noticed to be increased in both setups. That is because D_e is influenced by temperature [144]. Except near the end of the drying time, the difference between the curves of PITSD and AITSD seems to be identical though there is a notable difference in the physical data. There is a higher D_e in PITSD compared to AITSD because of the higher temperature inside PITSD due to heat back up from the TES unit, whereas, the higher air velocity deteriorates the temperature in AITSD.

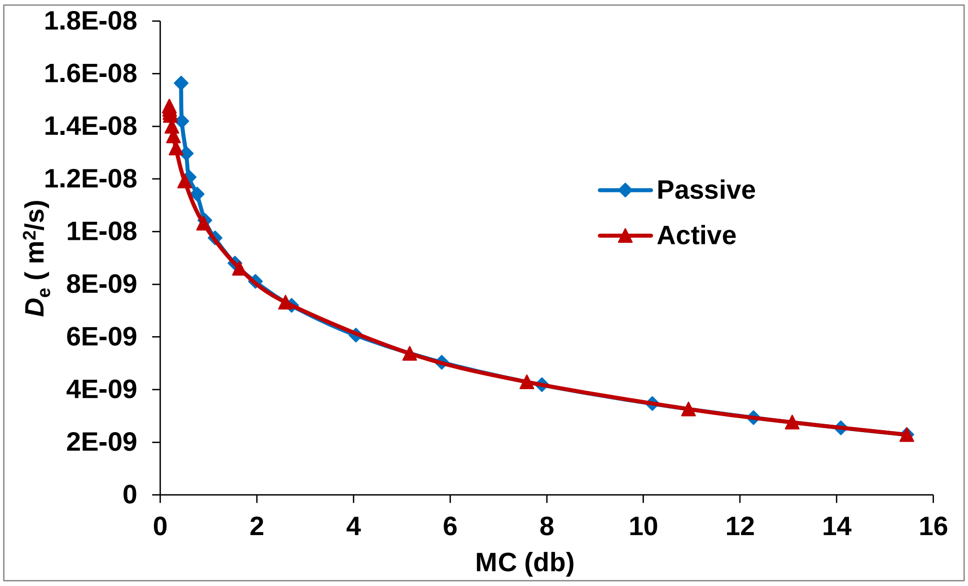


Fig. 4.28. Correlation between MC and D_e of ivy gourd in PITSD and AITSD with TES

Figure 4.29 portrays the trend of variation of h_m with MC during the drying of the sample slices. As shown in the implied **Fig. 4.29**, the trend of variation is related to a logarithmic function. The h_m is negatively related with the MC. It ascends with the reducing of MC. The same trend occurs in both setups, and the h (which is not shown here) followed the same pattern with D_e and h_m. The difference between PITSD and AITSD at the end of the drying might be due to less moisture on the surface of setup AITSD showing that sample slices in AITSD dried prior to that of setup PITSD because of extra mass flow rate.

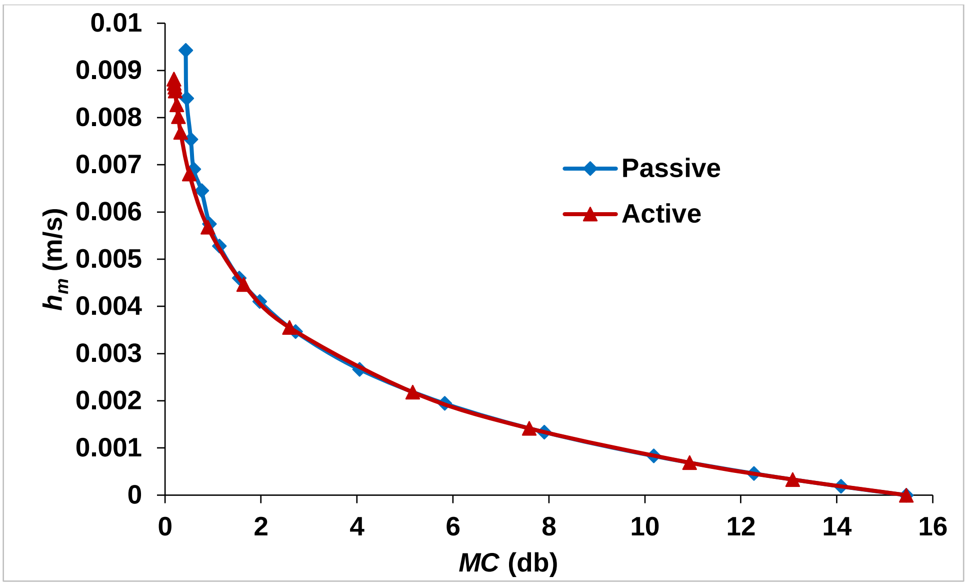


Fig. 4.29. Correlation between MC and h_m ivy gourd in PITSD and AITSD with TES

Table 4.6: Summary of correlation constants of with TES setups

Samples	Parameter	Setup	*y = a ln(MC) + b*		
			a	***b***	R^2
Ivy gourd	D_e	PITSD	-3×10^{-9}	1×10^{-8}	0.9756
		AITSD	-3×10^{-9}	1×10^{-9}	0.9999
	h_m	PITSD	-0.002	0.0061	0.9756
		AITSD	-0.002	0.0054	1
	h	PITSD	-2.667	6.9783	0.9756
		AITSD	-2.292	6.2755	0.9999
Pineapple	D_e	PITSD	-3×10^{-9}	8×10^{-9}	0.9998
		AITSD	-3×10^{-9}	9×10^{-9}	0.9939
	h_m	PITSD	-0.004	0.0091	1
		AITSD	-0.005	0.0102	0.9923
	h	PITSD	-5.069	10.456	0.9999
		AITSD	-5.567	11.76	0.992
Carrot	D_e	PITSD	-3×10^{-9}	8×10^{-9}	0.9856
		AITSD	-3×10^{-9}	9×10^{-9}	0.9845
	h_m	PITSD	-0.004	0.0077	0.9823
		AITSD	-0.004	0.0081	0.9848
	h	PITSD	-4.033	8.5518	0.9891
		AITSD	-4.218	9.3212	0.9825

4.4.3.8. Comparative analysis of the drying kinetics of the samples and the performance parameters of PITSD and AITSD with TES

The drying kinetics of ivy gourd, pineapple, and carrot dried in PITSD and AITSD supported with TES, and the performance parameters of the dryers have been comparatively assessed. **Table 4.7** shows the summary of the drying kinetics and performance parameters for PITSD and AITSD with TES. As can be noticed from the mentioned **Table 4.7**, there were noticeable improvements in the drying kinetics of the samples and the performance parameters of PITSD compared to AITSD.

Accordingly, the T_{co} and T_{ds} were lower in active than passive setup. The performance parameters like Q_a, SEC, SMER, η_c and η_c were noticeably increased in active mode compared to passive mode. The drying kinetics such as h_m, h, D_e, and DR were evaluated to be higher for active than passive mode setup, and there was significant improvement in E_a by using active mode provisions. The logarithmic correlations were noticed between D_e, h and h_m vs MC, and all of them increased with the decrease of MC. Drying time was reduced by using active mode provisions (2 h for each during drying ivy gourd and pineapple, and 3 h during drying carrot). Moreover, integrating TES helped the drying process complete in one day with only one day solar radiation.

Table 4.7: Comparative summary of the drying kinetics and performance parameters for PITSD and AITSD with TES

Parameter	**Samples**	**Passive**	**Active**	**Difference (%)**
η_c (%)	Ivy gourd	62.56	69.87	**11.69**
	Pineapple	58.18	67.79	**16.52**
	Carrot	59.7	67.8	**13.6**
η_d (%)	Ivy gourd	13.13	15.2	**12.59**
	Pineapple	9.7	11.9	**22.7**
	Carrot	11.1	14.2	**27.93**
D_e (m^2/s)	Ivy gourd	8.06 × 10-9	10.0×10^{-9}	**24.07**
	Pineapple	5.25 × 10-9	5.97×10^{-9}	**12.4**
	Carrot	7.2 × 10-9	8.0×10^{-9}	**11.1**

Parameter	Samples	Passive	Active	Difference (%)
h_m (m/s)	Ivy gourd	4.1×10^{-3}	5.5×10^{-3}	**34.14**
	Pineapple	4.89×10^{-3}	5.76×10^{-3}	**8.81**
	Carrot	6.2×10^{-3}	7.1×10^{-3}	**14.52**
h (W/m^2 K)	Ivy gourd	4.7	6.28	**33.62**
	Pineapple	5.6	6.47	**14.92**
	Carrot	7.1	7.9	**11.3**
DR (kg/h)	Ivy gourd	0.52	0.61	**17.3**
	Pineapple	0.408	0.45	**10.29**
	Carrot	0.49	0.56	**14.29**
E_a (kJ/mol)	Ivy gourd	39.85	36.35	**8.78**
	Pineapple	42.72	38.34	**10.23**
	Carrot	45.1	39.6	**12.2**
SEC (kWh/kg)	Ivy gourd	0.253	0.228	**9.88**
	Pineapple	0.322	0.273	**15**
	Carrot	0.276	0.219	**20.7**
SMER (kg/kWh)	Ivy gourd	3.95	4.38	**10.89**
	Pineapple	3.1	3.67	**18.39**
	Carrot	3.6	4.6	**27.8**
Q_a (W)	Ivy gourd	735.9	761.2	**3.41**
	Pineapple	813	902	**10.95**
	Carrot	722	807.4	**11.82**
T_{co} average (^{o}C)	Ivy gourd	45.48	42.6	**6.55**
	Pineapple	44.9	43.4	**3.34**
	Carrot	45.7	44.3	**6.55**
T_{ds} average (^{o}C) (trays)	Ivy gourd	41.49	40.59	**1 ^{o}C**
	Pineapple	41.9	39.87	**2 ^{o}C**
	Carrot	39.22	37.32	**1.9 ^{o}C**

Parameter	Samples	Passive	Active	Difference (%)
T_{TES} average (°C)	Ivy gourd	42.6	41.75	**1 °C**
	Pineapple	42.68	41.26	**1.42 °C**
	Carrot	40.16	38.96	**1.2 °C**
MC (db)	Ivy gourd	initial	final	**-**
	Pineapple	15.32	0.144	**-**
	Carrot	7.91	0.417	**7.91**
	Ivy gourd	9.13	0.478	**9.13**
Total time taken to dry (h)	Pineapple	16	14	**12.5**
	Carrot	16	14	**12.5**
	Ivy gourd	15	12	**20**

4.5. Evaluation of 3E parameters

In this specific section, aiming to make the analysis more accurate, the 3E parameters of drying agriproducts (ivy gourd, pineapple, and carrot) in PITSD and AITSD are evaluated for three different configuration of the setups. The first one is for drying carrot in passive and active setups without TES (section 4.5.1). The second one is for drying ivy gourd in passive setup without and with TES (section 4.5.2), and the last one is for pineapple in active setup without and with TES (section 4.5.3).

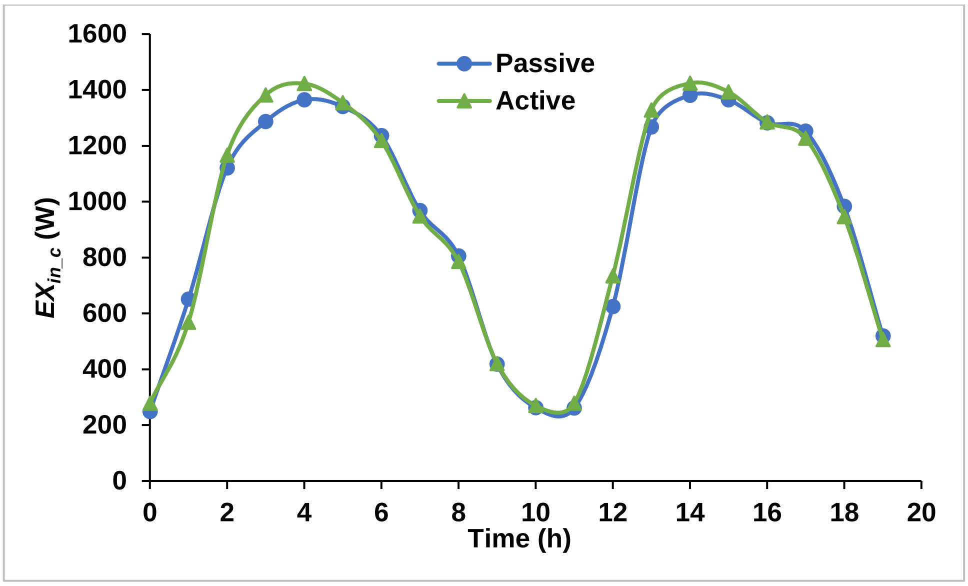
4.5.1. Evaluation of 3E parameters for PITSD and AITSD without TES

4.5.1.1. Exergy parameters

Exergy inflow (EX_{in_c}), outflow (EX_{out_c}), and loss (EX_{l_c}) of the collector

The EX_{in_c} for drying carrot in PITSD and AITSD was estimated and shown in **Fig. 4.30 (a)**. EX_{in_c} is influenced by the collector area, rate of mass flow, the solar intensity in addition to the T_{atm}. In the noontime hour when it was expected that the solar radiation would be at its strongest intensity, pick values for EX_{in_c} were observed. Accordingly, in the PITSD, the maximum, average, and minimum EX_{in_c} values were 1380.92, 931.65, and 248.38 W, respectively, and in AITSD, the same were 1423.62, 1004.87, and 269.94 W. In comparison to PITSD, there was a 7.86% improvement in average EX_{in_c} for the AITSD. Similarly, the data taken from the drying experiment was also used to evaluate the EX_{l_c}. Because the plot of EX_{l_c} is similar to that of EX_{in_c}, it is not shown here. The maximum, average, and minimum EX_{l_c} values for PITSD and AITSD were 1320.07, 896.16, and 245.96 W; 1382.84, 979.95, and 267.95 W, respectively.

(a)



(b)

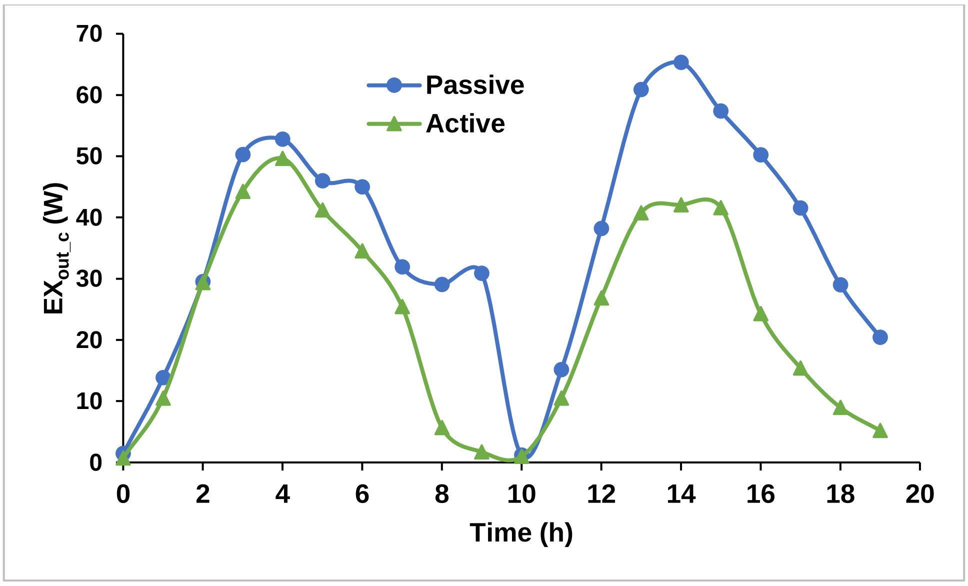


Fig. 4.30. Collector's (a) exergy inflow (b) exergy outflow of drying carrot in PITSD and AITSD without TES

Figure 4.30 (b) shows the EX_{out_c} of PITSD and AITTSD during drying carrot. The EX_{out_c}, shown in **Fig. 4.30 (b)**, reaches its maximum around noon. It increases up to the maximum value, then gradually declines as the solar intensity increases. In the PITSD, the maximum, average, and minimum EX_{out_c} values were 65.3, 35.5, and 1.2 W, respectively. And in the AITSD, the same were 49.62, 24.92, and 0.98 W, respectively. There was higher mean EX_{out_c} in PITSD compared to AITSD that might be due to higher temperature of collector outlet in the PITSD.

Estimating collector's exergy efficiency (η_{EX_c})

The η_{EX_c} is evaluated and shown in **Fig. 4.31**. Since the exergy inflow and outflow are the main determining parameters of η_{EX_c}, the style of variation is similar to **Fig. 30 (a)** and **(b)**. As a result, the mean η_{EX_c} for the PITSD and AITSD were 3.62 and 2.27 %, respectively, and the corresponding values were in 0.45 to 6.12% and 0.36 to 3.77 %, respectively. This study also agrees with the data presented in existing studies [64, 139], as the values presented in those studies were between 0.21 to 5.12%, respectively.

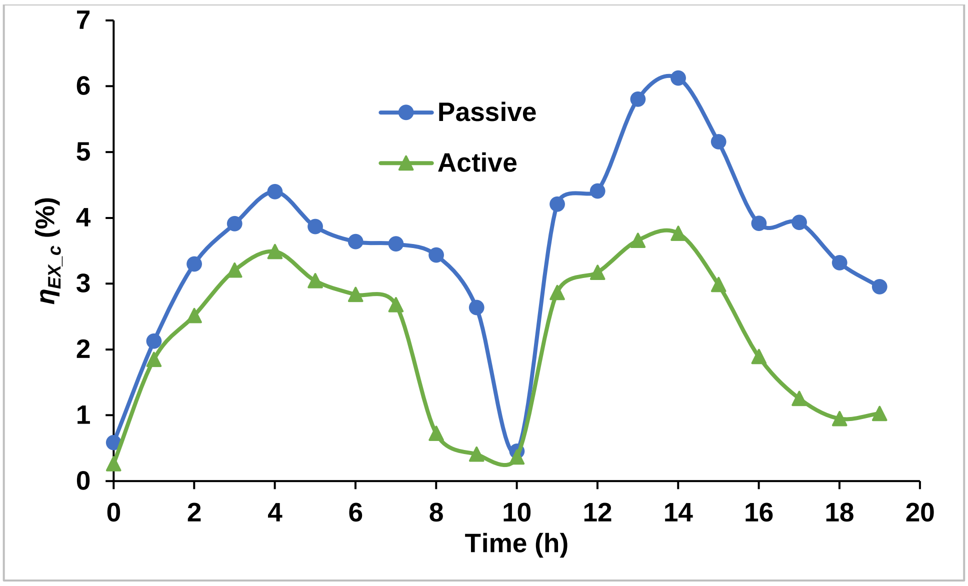


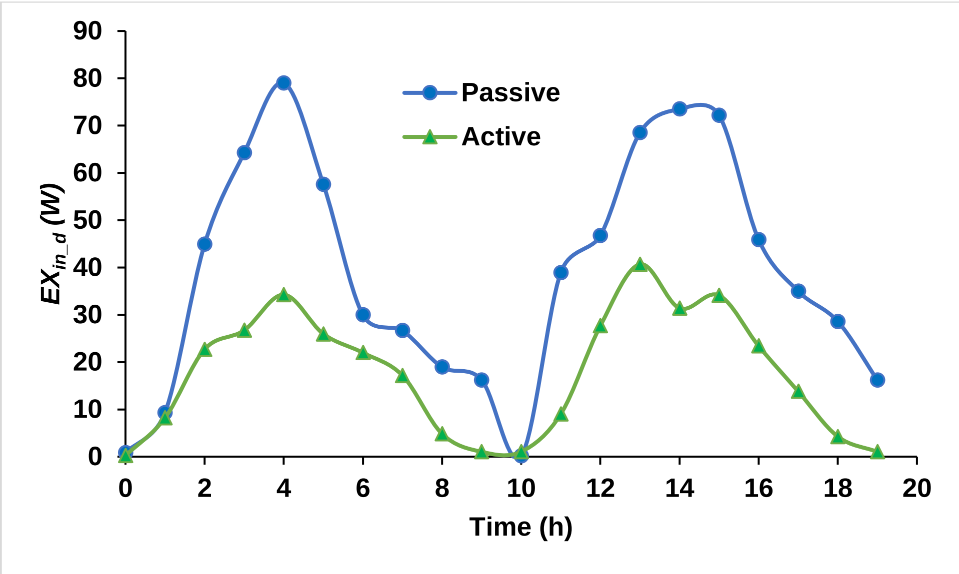
Fig. 4.31. Collector's exergy efficiency of drying carrot in PITSD and AITSD without TES

Evaluating exergy inflow (EX_{in_d}), outflow (EX_{out_d}), and loss (EX_{out_d}) of drying cabinet

Figures 4.32 (a) and **(b)** show the EX_{in_d} and the EX_{out_d} during drying carrot in ITSD without TES, respectively. Both **Figs**. demonstrate that the EX_{in_d} and EX_{out_d} varied along a similar trend to the variation of solar radiation. For the PITSD and AITSD, the average values of EX_{in_d} were 38.67 and 17.47 W, respectively. EX_{in_d} is observed to be higher for the PITSDS than AITSD. Specifically, EX_{in_d} is determined by the variation of the temperature between inlet and outlet of the drying section.

Similarly, average EX_{out_d} for the PITSD and AITSD was estimated to be 16.21 and 10.27 W, respectively. EX_{out_d} is observed to be higher for the PITSD than AITSD just like EX_{in_d} does. The PITSD has a higher outlet temperature than AITSD, which could explain the higher EX_{in_d} and EX_{out_d} in PITSD.

(a)



(b)

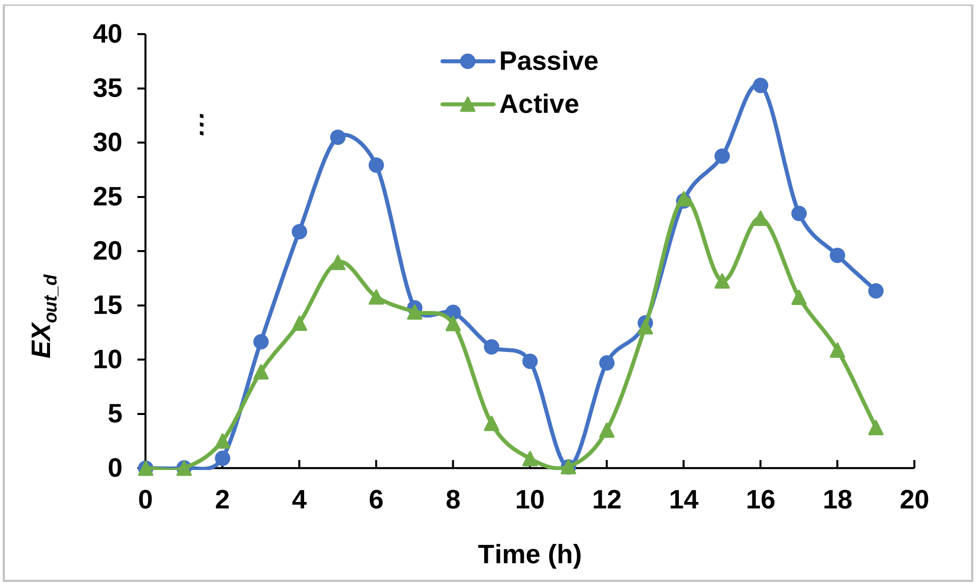


Fig. 4.32. Drying section's exergy (a) inflow (b) outflow of PITSD and AITSD without TES

Estimating the drying section's exergy loss (EX_{l_d}) and exergy efficiency (η_{EX_d})

The graph of EX_{l_d} (not shown here) behaved with time similar to the graph of EX_{in_d}. For the PITSD, EX_{l_d} was computed in the range of 0.028 to 48.5 W while it was computed to range from 0.077 to 15.83 W for the AITSD. Their respective averages were 22.47 and 7.2 W for the same. Compared to PITSD, the AITSD reduced the loss of exergy by about 67.96%.

The EX_{out_d} and EX_{in_d} are the major factor affecting the η_{EX_d}. **Fig. 4.33** shows a typical variation of η_{EX_d} over time. The η_{EX_d} was observed to be increasing with time for both passive and active setups as shown in **Fig. 4.33**. The η_{EX_d} values were evaluated for the PITSD and AITSD in the ranged of 3.79% to 80.63 % and 6.1 to 92.46%, respectively. It average values for the same were 43.31 % and 58.4%, respectively. Accordingly, η_{EX_d} of the drying section was improved by 34.84 % in the AITSD compared to the PITSD. This study's findings are generally in accordance with existing literature reported in [68] (3.7 – 75.15%) and [139] (6.34 - 94.35%).

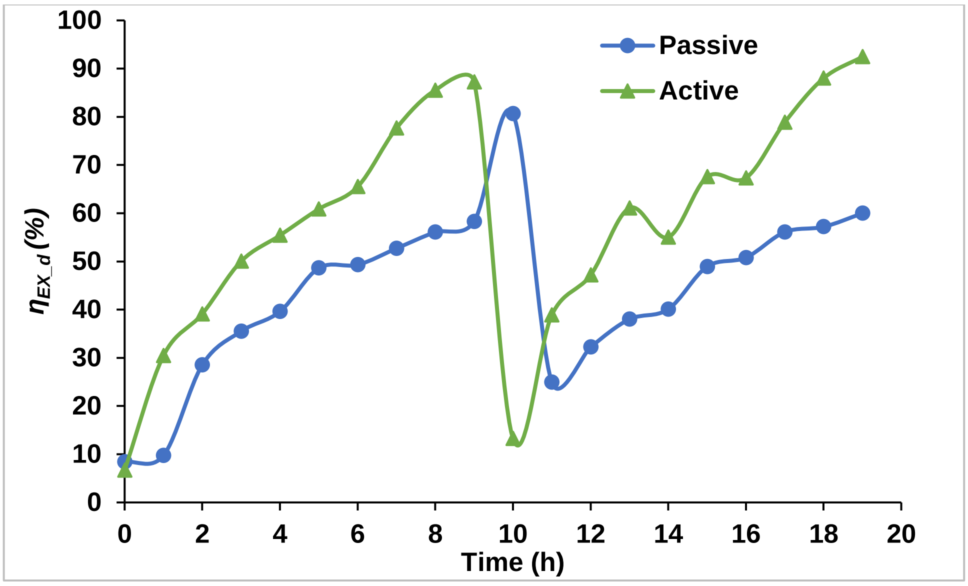


Fig. 4.33. Drying section's exergy efficiency for drying carrot in PITSD and AITSD without TES

Exergy's sustainability indicators

Using sustainability indicators of exergy, such as the ratio of waste exergy (WER), environmental impact factor, sustainability index (SI), improvement potential (IP), an effective drying facility can be formulated. **Table 4.8** summarizes the estimated values of exergy sustainability indicators for drying carrot in PITSD and AITSD. As indicated in **Table 4.8**, the mean values of WER, IP, EIF, and SI for the PITSD were 0.57%, 12.74 W, 2.93%, and 2%, while the same for the AITSD were 0.42%, 3.75 W, 1.67%, and 3.75%, respectively. Accordingly, by using AITSD, there was an improvement of 26.32% in WER , 76.45% in IP, 43% in EIF, and 85% in SI in comparison with the PITSD, that is matching with the results reported by Mugi et al. [75, 133].

Table 4.8: Exergy sustainability indicators of PITSD and AITSD with TES

Variable	**PITSD**		**AITSD**		**Variation (%)**	**Remark**
	Avg.	Range	Avg.	Range		
WER (%)	0.57	0.194 - 0.962	0.42	0.075 - 0.94	26.32	Improved
IP (W)	12.74	4.35 - 21.62	3.00	0.54 - 6.72	76.45	Improved
EIF (%)	2.93	0.24-25.4	1.67	0.0.082 - 13.91	43.00	Improved
SI (%)	2.00	1.04 – 5.16	3.75	1. 07- 13.26	87.5	Improved

4.5.1.2. Analysis of environmental impact of drying carrot in a PITSD and AITSD without TES

Embodied energy (E_e)

From the materials and parts used in constructing the dryer, E_e (embodied energy) has been calculated for PITSD and AITSD and summarized in **Table 4.9**. Due to the additional mass of parts used to promote mass flow rate, it is indicated that AITSD has a higher E_e than PITSD, as shown in **Table 4.9** (PITSD = 536.34 kWh and AITSD = 898.84 kWh).

Table 4.9. E_e of PITSD and AITSD without TES

Materials	**Energy density (kWh/kg)** [79, 81, 86, 114, 146]	**Mass of component (kg)**		**E_e (kWh)**		**Remark**
		PITSD	**AITSD**	**PITSD**	**AITSD**	
Copper	19.61	1.85	1.85	36.28	36.28	Collector
Glass	7.28	0.95	0.95	6.92	6.92	Glass cover
Galvanized iron	9.634	12.6	12.6	121.39	121.39	Outer cover
black paint	25.11	0.58	0.575	14.44	14.44	Coatings
wood	0.66	2.1	2.1	1.39	1.39	Trays
Plastic mesh	19.44	0.45	0.45	8.75	8.75	
Glass wool	4.04	4.25	4.25	17.17	17.17	Insulations
Thermocol	24.61	0.51	0.51	12.5511	12.55	
Mild steel	8.89	34.75	34.75	308.93	308.93	Frames
Steel	8.89	0.96	0.96	8.53	8.53	Fittings
Galvanized iron	9.636	0	6.13	0	59.07	

DC fan (plastics , copper wires)	19.4	0	0.36	0	6.99	Active mode provisions
	19.61	0	0.127	0	2.49	
Solar cell (kWh/m^2)	1130.6	0	0.26	0	293.96	
Total		**58.995**	**65.872**	**536.34**	**898.84**	

Payback period of energy (EPBP)

E_e and E_{AO} of a dryer with a life span of 30-year are used to determine the EPBP. The quantity of daily solar energy output (E_{DA}) determines the E_{AO}. Accordingly, the mean values of E_{AO} for setup PITSD and AITSD was estimated as 402.19 kWh/year and 504 kWh/year, respectively. Accordingly, the EPBP estimated for the PITSD and AITSD were 1.33 and 1.78 years, respectively. The EPBP for AITSD is higher than PITSD because of the extra mass of the materials used for promoting the air flow rate.

Estimating the emission of CO_2, mitigation of carbon and earned carbon credit

As depicted in **Table 4.10**, by assuming a lifespan of 30 years for the solar dryer, CO_2 emissions, mitigation, and credits were estimated. A graphical illustration of how CO_2 emission, mitigation, and credit, vary with the life of the dryer are presented in **Fig. 4.34**. Because of extra mass of materials to construct the active provision, the AITSD emits more CO_2 than the PITSD. However, the carbon mitigation for the AITSD is higher than for the PITSD due to higher E_{AO} for the AITSD. Furthermore, the AITSD has a larger carbon credit than the PITSD because of the difference in annual energy output. The CO_2 emissions for both setups decreased as the dryer life increased, and both carbon mitigation and credit earned increased. The results of the current study were in accordance with the study by Vijayan et al. [154], having the EPBP, CO_2 mitigation, and carbon credit values of an AITSD over 35 years were 2.21 years, 33.52 tons, and $144.772 - $579.087, respectively.

Table 4.10. Emission of CO_2, carbon mitigation and carbon credit earned

Setup	**Life of dryer (yr)**	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**
PITSD	Emission of CO_2 (kg/yr)	365.1	182.5	121.7	91.27	73.01	60.84	52.15	45.63	40.56	**36.50**
	Mitigation of carbon (ton/yr)	2.16	5.48	8.79	12.11	15.42	18.73	22.04	25.36	28.68	**31.99**

	Carbon credit($) on base of $20	43.26	109.5	175.8	242.1	308.4	374.7	440.9	507.2	573.5	**639.8**
AITSD	Emission of CO_2 (kg/yr)	455.4	227.7	151.8	113.9	91.09	75.9	65.05	56.92	50.6	**45.54**
	Mitigation of carbon (ton/yr)	2.066	6.15	10.25	14.35	18.45	22.55	26.65	30.74	34.84	**38.94**
	Carbon credit($) on base of $20	41.2	123.3	205.0	287.0	369.0	450.9	532.9	614.9	696.8	**778.8**

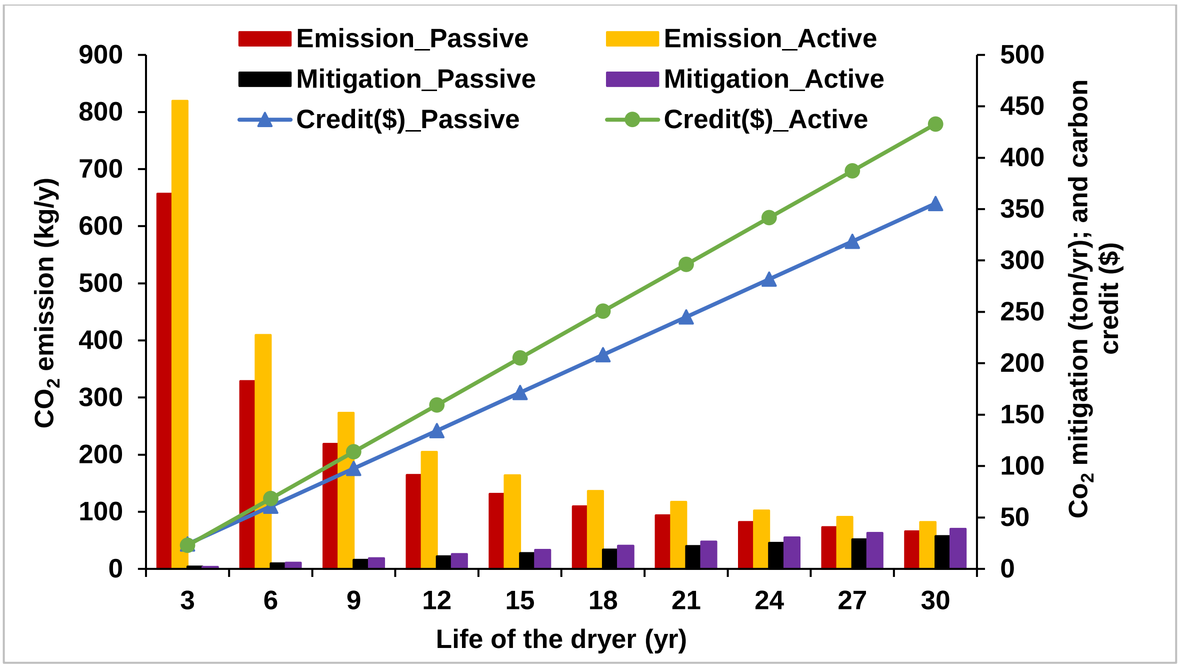


Fig. 4.34. Annual emission of CO_2, carbon mitigation and carbon credit earned of PITSD and AITSD without TES during drying carrot

4.5.1.3 Estimating economic parameters

This study examined the construction of two solar dryers (PITSD and AITSD) with a lifetime of 30 years (L_d) at capital costs of 95000 and 110000 INR ($ 1218.77 and $1411.21), respectively. **Table 4.11** summarizes the economic significance of drying carrots in PITSD and AITSD. Both setups were fully loaded (5 kg) for the analysis. The slices of carrot were dried in the PITSD and AITSD setups from 9.13 (db) to 0.478 (db) in 15 and 12 hours, respectively. A total of 2160 active sunshine hours were assumed (9 months x 240 days) for the analysis. The prices of fresh carrot and the final dried one were 50 and 200 INR, respectively. The annual dryer cost (Cy) of PITSD and AITSD was 3995.10 and 5995.65 INR, respectively. As a result of modifying the AITSD for mass flow rate promotion, the C_y was higher for AITSD than the PITSD. For the PITSD and AITSD, the annual drying cost per kg of carrot was determined to be 7.07 and 4.7 INR, respectively. PITSD was estimated to have an economic payback period (N) of 1.02 years, while AITSD had an N of 0.66 years. In comparison to the PITSD, the AITSD reduced the N by 35.29% (0.36 years).

Table 4.11. Summary of economic impact parameters of drying carrot in PITSD and AITSDs

Variable	PITSD	AITSD
Dryer's capital cost (C_T) (INR)	95000 INR ($ 1,218.77)	110000 INR ($ 1411.21)
Total active hours (h)	2160	2160
The dryer's capacity (kg)	5	5
Annually dried carrots (kg /year)	700	1300
Yearly cost (C_y) (INR)	4951.68 ($63.52)	5949.32 ($76.82)
Fresh carrots' price (INR/kg)	50 INR ($0.64)	50 INR ($ 0.64)
Dried carrots' price (INR/kg)	200 INR ($ 2.56)	200 INR ($ 2.56)
Annual drying cost (C_d) (INR/kg)	7.07	4.7 INR ($0.05)
Period of payback (N) (yr)	1.02	0.622

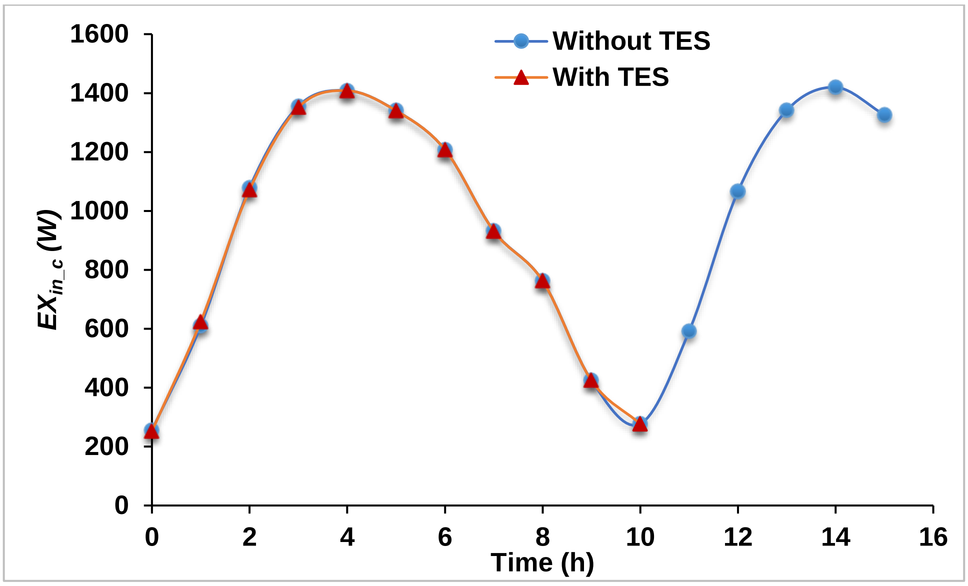
4.5.2. Evaluation of 3E parameters for PITSD without and with TES

4.5.2.1. Exergy parameters

Collector exergy inflow (EX_{in_c}) and outflow (EX_{out_c})

The EX_{in_c} has been evaluated for PITSD without and with TES during drying ivy gourd and displayed in **Fig. 4.35 (a)**. The EX_{in_c} is a function of collector area, mass flow rate, solar intensity and temperature of ambient air. Similar to all other solar-dependent parameters, EX_{in_c} for the setup with TES was evaluated for one-day sunshine drying hours, while two days sunshine hours for the setup without TES. Maximum values of EX_{in_c} were noticed at noon where the highest solar intensity was supposed to be attained. The minimum, average and maximum EX_{in_c} without TES setups were evaluated to be 255.7, 974.9 and 1419 W and the same values for the with TES unit were 252.7, 877.5 and 1404.9 W, respectively. There was no significant variation been noticed between the EX_{in_c} of the two setups. Similarly, exergy loss of the collector (EX_{l_c}) 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 EX_{in_c}. The minimum, average and maximum EX_{I_c} were 253.9, 934.8, 1363.3 W (without TES) and 251.2, 852.4 and 1360.2 W (with TES unit), respectively.

(a)



(b)

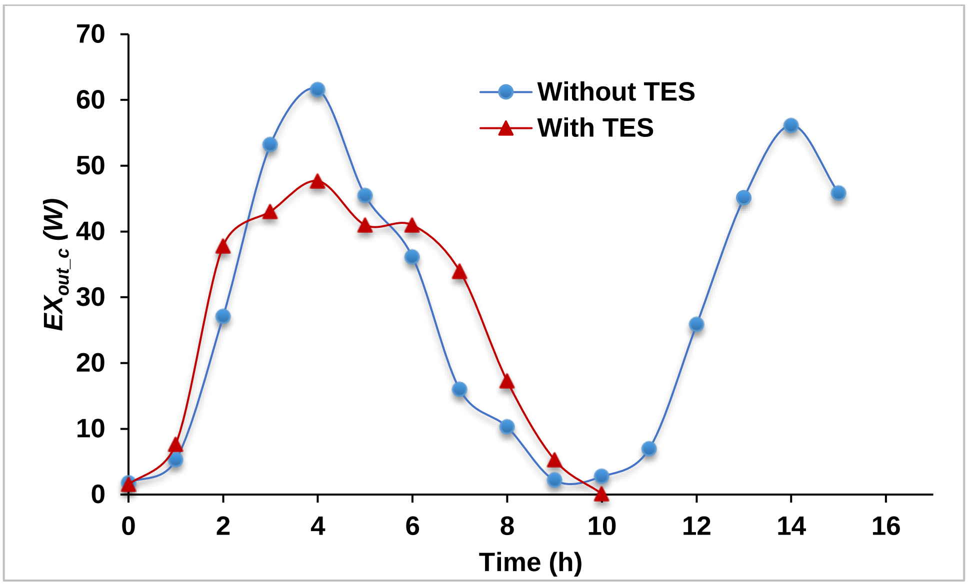


Fig. 4.35. Exergy (a) inflow and (b) outflow of collector without and with TES setups

The EX_{out_c} of passive ITSD (without and with TES) was evaluated with time and is described in **Fig. 4.35 (b)**. From **Fig. 4.35 (b)**, the maximum outflow is achieved at noon. The trend of variation was observed to be increasing with an increasing rate before the maximum value attained, and then gradually started to decline with the solar intensity. This is because EX_{out_c} is dependent on the temperature of ambient air, collector outlet, and inlet. Slight variations were observed in the values of EX_{out_c} between the two setups. This could be because of variation in the temperature of ambient air.

Exergy efficiency of collector (η_{EX_c})

Figure 4.36 mentions the η_{EX_c}. The trend of variation is almost similar of **Fig. 4.35 (a)** and **(b)** because η_{EX_c} dependent on the exergy inflow and outflow. On the other hand, EX_{in_c} is a function of solar radiation that influences the exergy efficiency. The average η_{EX_c} for the setup without and with TES was 2.33 and 2.12 %, where its corresponding values were in the range of 0.513-3.97 % and 0.04-3.79 %, respectively. The results were comparatively equivalent for both setups. The values in this study agree with the data mentioned in the existing studies [35, 45] as the values mentioned were in the range of 0.21 – 5.12%, and 0.81%, respectively.

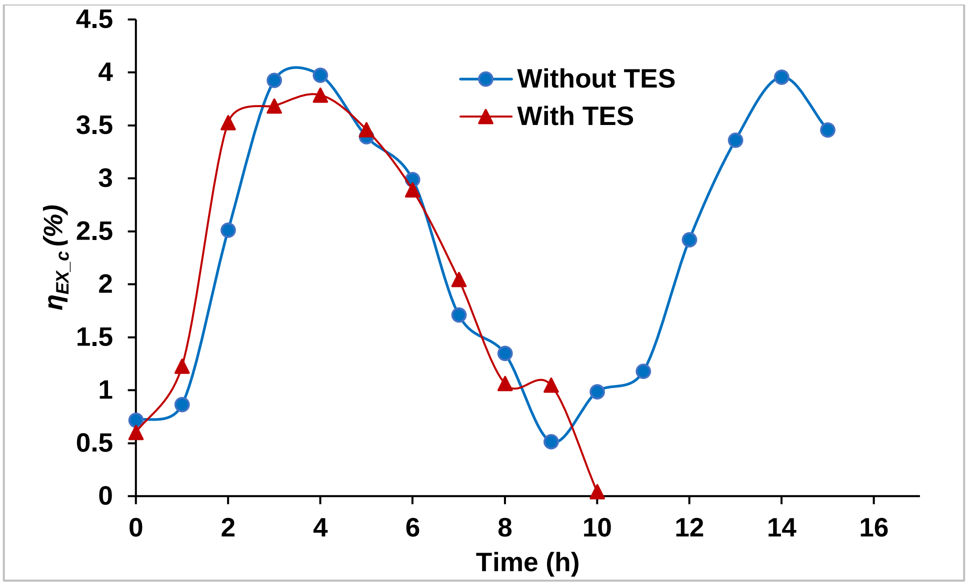
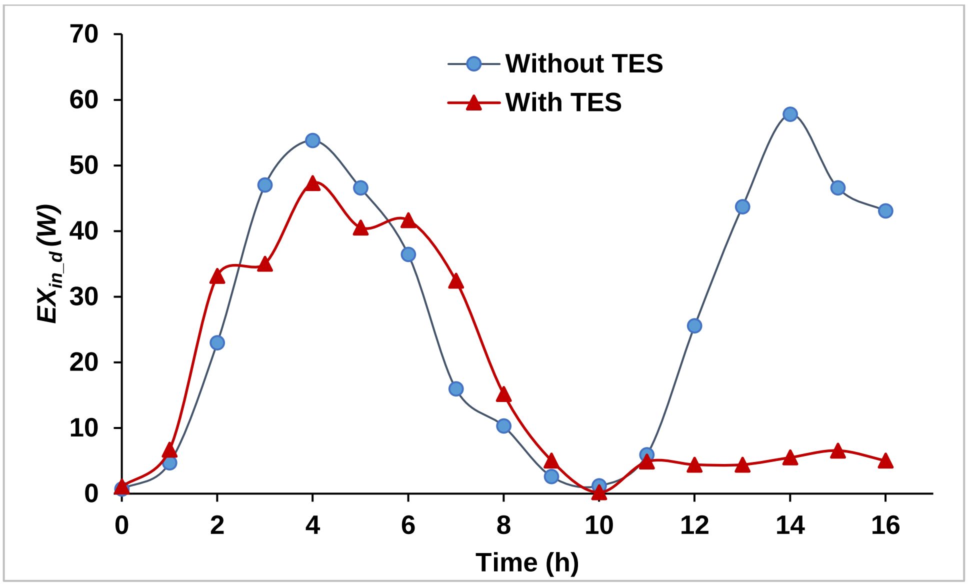


Fig. 4.36. Exergy efficiency of collector for PITSD without and with TES during drying ivy gourd

Exergy inflow (EX_{in_d}) and outflow (EX_{out_d}) of drying section

Figure 4.37 (a) portrays the EX_{in_d} with time. As indicated in the mentioned **Fig.**, the EX_{in_d} was seen to be varied similar to the trend of solar radiation variation for both setups. But EX_{in_d} became nearly constant after the sunset for the setup with TES. The heat storage unit could be the reason as it maintained the temperature by discharging after the sunshine hour. The average, minimum, and maximum EX_{in_d} for the setups without and with TES were evaluated to be 27.34 & 17 W, 0.6694 & 0.1875 W and 57.77 & 47.31 W, respectively. The EX_{in_d} is a function of the difference between outlet and inlet temperatures of the drying section. The inlet temperature of the setup with TES is greater than that of without TES, which could be a reason for higher EX_{in_d} in without than with TES setup.

(a)



(b)

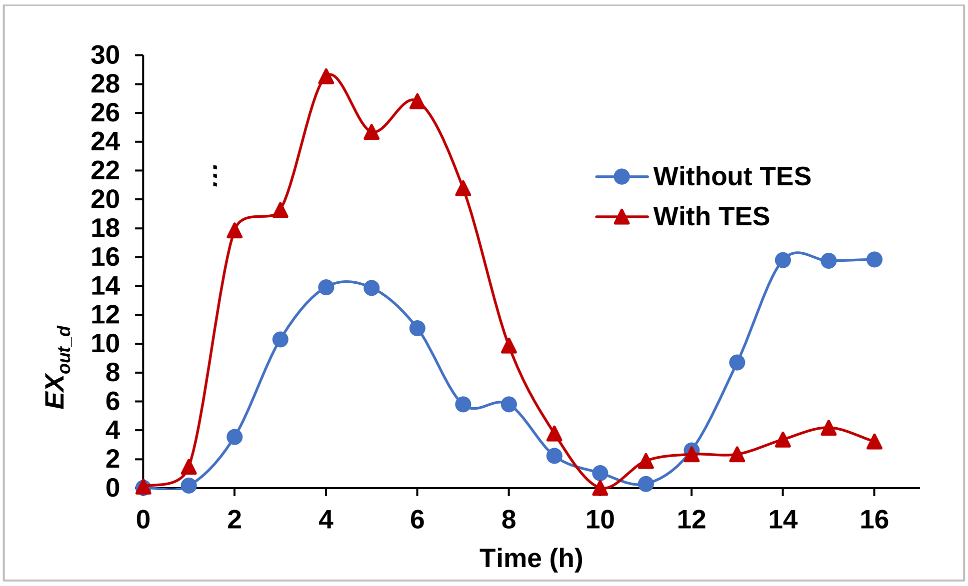


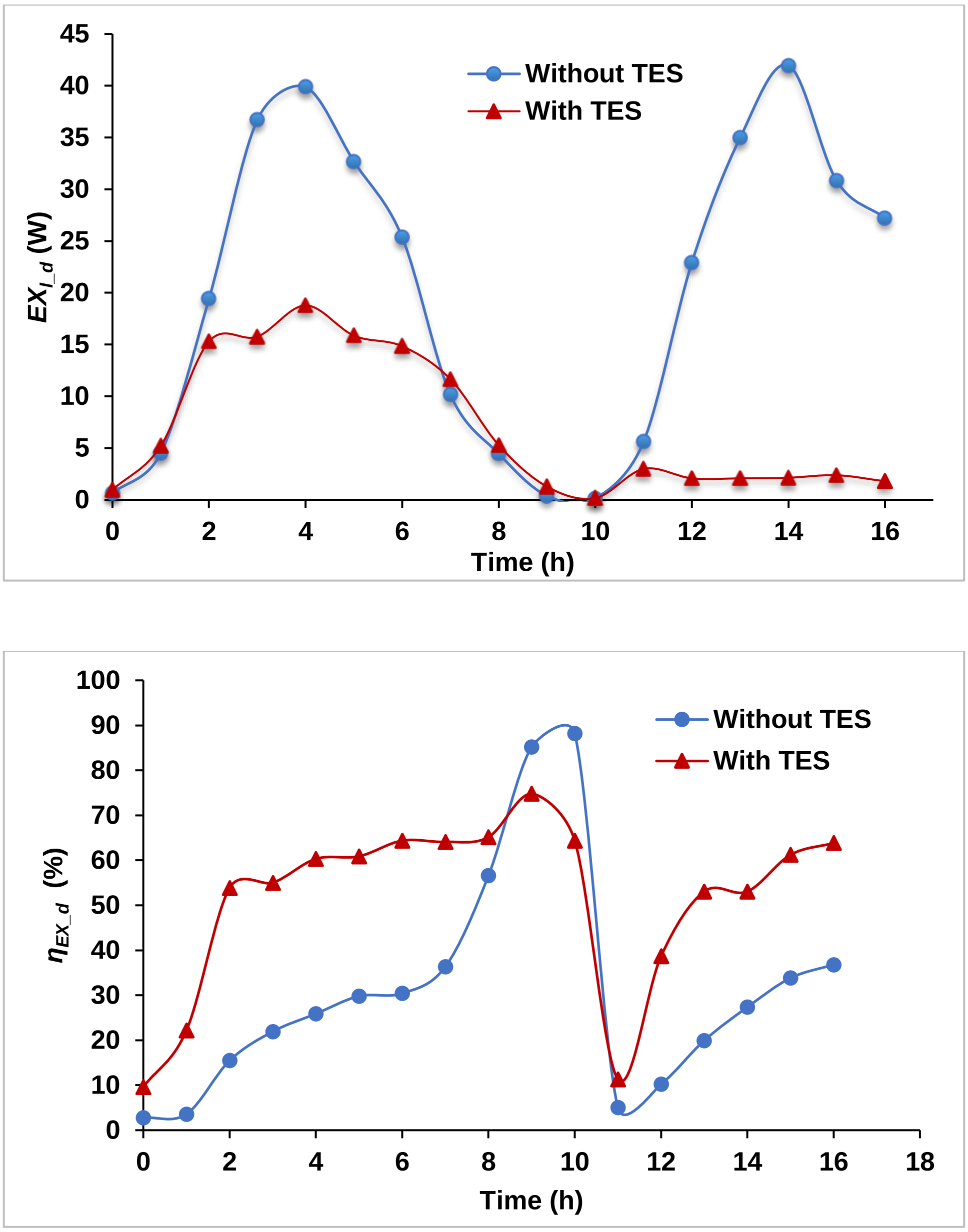
Fig. 4.37. Exergy (a) inflow and (b) outflow of drying section of PITSD without and with TES

Similarly, the EX_{out_d} is evaluated and described in **Fig. 4.37 (b)**. It is a function of the inlet and outlet temperature of the drying section. The average values of EX_{out_d} for the setups without and with TES were 7.46 and 10 W, respectively. Its estimated ranges of values for the same were 0.087-15.85 W and 0.02126-28.54 W, respectively. The setup with TES showed an improvement of 34.05% (2.56 W) compared to the setup without TES.

Exergy loss (EX_{l_d}) and efficiency (η_{EX_d}) of the drying section

The EX_{l_d} and its variation with time is reported in **Fig. 4.38 (a)**. As can be noticed from **Fig. 4.38 (a)**, EX_{l_d} increased with time until noon and started to fall afterward. The computed ranges of the values of EX_{l_d} for the setups without and with TES were 0.1407 - 41.97 W and 0.1663 - 18.78 W, respectively. The average values for the same were 19.87 and 6.97 W, respectively. The setup with TES reduced the loss of 12.9 W (which is a 64.92% reduction in exergy loss) compared to the setup without TES.

(a)



(b)

Fig. 4.38. Exergy (a) loss and (b) efficiency of drying section without and with TES

The η_{EX_d} is mainly influenced by the exergy outflow and inflow of it. **Fig. 4.38 (b)** describes the characteristic variation of η_{EX_d} with time. From **Fig. 4.38 (b)**, η_{EX_d} for both without and with TES setups were observed to be increasing with time. The evaluated values of η_{EX_d} for the setups without and with TES were in the range of 2.79-88.16% and 9.634-74.79% and the averages were 31.12 and 51.52%, respectively. The setup with TES showed an improvement of 65.56 % of η_{EX_d} of the drying section compared to the setup without TES. The result in the current study is in good agreement with the existing literature reported by Bhardwaj et al. [68] (3.7 – 75.15%) and Mugi et al. [139] (6.34 - 94.35%).

Sustainability indicators of exergy

The sustainability indicators of exergy namely WER, IP, SI, and EIF, were estimated to figure out the exergy efficiency and exergy loss of the drying section with the reference to exergy input. The values are summarized in **Table 4.12**. From **Table 4.12**, the values of IP, WER, SI and EIF for the setups without and with TES were in the range of 0.3539–19.32 W & 1.758–6.3 W, 0.1184–0.9720 W & 0.2521–0.037%, 1.029–8.443 & 1.107–3.967 %, and 0.1343-34.80 & 0.3371-9.38, respectively. The average values of the IP for the same were 13.69 and 3.38 W, respectively. The setup without TES has higher IP than the setup with TES showing that there was low exergy loss in with TES, which is in good agreement reported by Mugi et al. [78].

Similarly, the average WER and SI for the setup without TES were 0.6886 % and 2.1 % and the same for with TES were 0.4848 % and 2.321%, respectively. The WER is higher for the setup without TES as it is a function of exergy loss, whereas SI is higher for the setup with TES indicating that there is higher exergy efficiency for the setup with TES than that of without TES. The results of the present study are in good agreement with the existing literature by Mugi et al. [2, 35] as their WER and SI are in the range of 0.06 to 0.83 and 1.19 to 17.05, respectively. Similarly, EIF was assessed for both setups. The average values of EIF for the setups without and with TES were 7.007 and 1.811%, respectively. The setup with TES minimized the impact on the environment by 74.15% compared to the setup without TES. This is because the setup with TES has lower exergy loss compared to the setup without TES.

Table 4.12: Summary of sustainability indicators for without and with TES setups during drying ivy gourd

Property	**Without TES**		**With TES**		**Variation (%)**	**Remark**
	Average	Range	Average	Range		
IP (W)	13.69	0.3539-19.32	3.380	1.758-6.300	71.44	Decrease
WER (%)	0.6886	0.1184-0.9720	0.4848	0.2521-0.9037	29.6	Decrease
SI (%)	2.1	1.0290-8.4430	2.321	1.107-3.967	10.52	Increase
EIF (%)	7.007	0.1343-34.80	1.811	0.3371-9.38	74.15	Decrease

4.5.2.2. Environmental analysis

Embodied energy

The E_e of the solar dryer without and with TES was evaluated from the components and materials used to construct the solar dryer and described in **Table 4.13**. From the stated **Table 4.13**, the E_e for the setups without and with TES was 563.75 and 1008.67 kWh, respectively. The setup with TES has higher E_e than that of without TES because of the extra mass of TES.

Table 4.13. Embodied energy of PITSD without and with TES setups

No	**Components**	**Materials**	**Energy density (kWh/kg)** [5, 11, 37, 46]	**Mass of component (kg)**		$\boldsymbol{E_e}$ **(kWh)**	
				Without TES	**With TES**	**Without TES**	**With TES**
1	TES	PCM (paraffin wax)	9.1	-	21	-	191.1
		Al (fins + tubes)	55.28	-	1.25	-	69.1
		Polycarbonate	10.16	-	5	-	50.8
		Glass	7.28	-	4	-	29.12
		Thermocol	24.61	-	0.25	-	6.15

No	Components	Materials	Energy density (kWh/kg) [5, 11, 37, 46]	Mass of component (kg)		E_e (kWh)	
				Without TES	With TES	Without TES	With TES
		Galvanized iron	9.64	-	10.25	-	98.77
2	Absorber plate	copper	19.61	1.8	1.8	35.28	35.28
3	Glass cover	Glass	7.28	0.9	0.9	6.55	6.55
4	Outer covers	Galvanized iron	9.634	12.4	12.4	119.48	119.48
5	Coatings	black paint	25.11	0.56	0.56	14.06	14.06
6	Trays	wood	0.66	0.5×4 = 2	0.5×4 = 2	1.32	1.32
		Plastic mesh	19.44	0.5×4 = 2	0.5×4 = 2	38.88	38.88
7	Insulation	Glass wool	4.04	4.2	4.2	16.98	16.98
		Thermocol	24.61	0.45	0.45	11.075	11.075
8	Frames	Mild steel	8.89	35.14	35.14	312.332	312.332
9	Fittings (nuts, bolts, screw and rivets)	steel	8.89	0.85	0.85	7.556	7.556
Total				**60.3**	**102.05**	**563.51**	**1008.67**

Energy payback period

The EPBP of a PITSD without and with TES during drying ivy gourd is estimated from the E_e and the E_{AO} of the solar dryer with a lifetime of 25 years. On the other hand, the E_{AO} is a function of the daily energy output of the solar dry. The E_{AO} for setups without and with TES was 540.96 and 669.02 kWh/year, respectively. The EPBP for the setups without and with TES was estimated to 1.04 and 1.5l years, respectively. The setup with TES showed an improvement of 45.19% in EPBP compared to the setup without TES.

CO_2 emission, mitigation and credit

Considering the lifespan of the solar dryer to be 25 years, CO_2 emission, mitigation and credit of drying ivy gourd in a PITSD without and with TES were estimated and summarized in **Table 4.14**. The variation of CO_2 emission, mitigation and credit with the lifespan of the dryer is depicted in **Fig. 4.39**. There is a larger emission of CO_2 in the setup with TES than that without TES. This could be because of higher E_e due to the mass of TES construction materials. The carbon mitigation is higher for the setup with TES than that without TES. This is happened due to higher yearly energy output for the setup with TES than the setup without TES. Similarly, the setup with TES has larger CO_2 credit than the setup without TES.

In general, the CO_2 emission decreased, mitigation and credit increased with the increase of the life of the dryer for both setups. A report by Vijayan et al. [154] supports the results of the current study as their values of the energy payback, CO_2 mitigation and carbon credit were 2.21 years, 33.52 tons, and between $144.772 to $579.087, respectively, for a lifetime of 35 years.

Table 14. CO_2 emission, mitigation and credit of drying ivy gourd in PITSD without and with TES

Type setup	Life of dryer (year)	3	6	9	12	15	18	21	25
Without TES	CO_2 emission (kg/yr)	383.6	191.8	127.8	95.90	76.72	63.93	54.80	46.03
	CO_2 mitigation (ton/yr)	2.16	5.48	8.79	12.11	15.42	18.73	22.05	26.47
	Carbon credit($) 20$ base	43.26	109.5	175.8	242.1	308.4	374.6	440.9	529.3
With TES	CO_2 emission (kg/yr)	455.4	227.7	151.8	113.8	91.08	75.9	65.05	54.6

	CO_2 mitigation (ton/yr)	2.06	6.15	10.25	14.35	18.45	22.55	26.65	32.1
	Carbon credit($) 20$ base	41.1	123.1	205	287	368.9	450.9	532.9	642.2

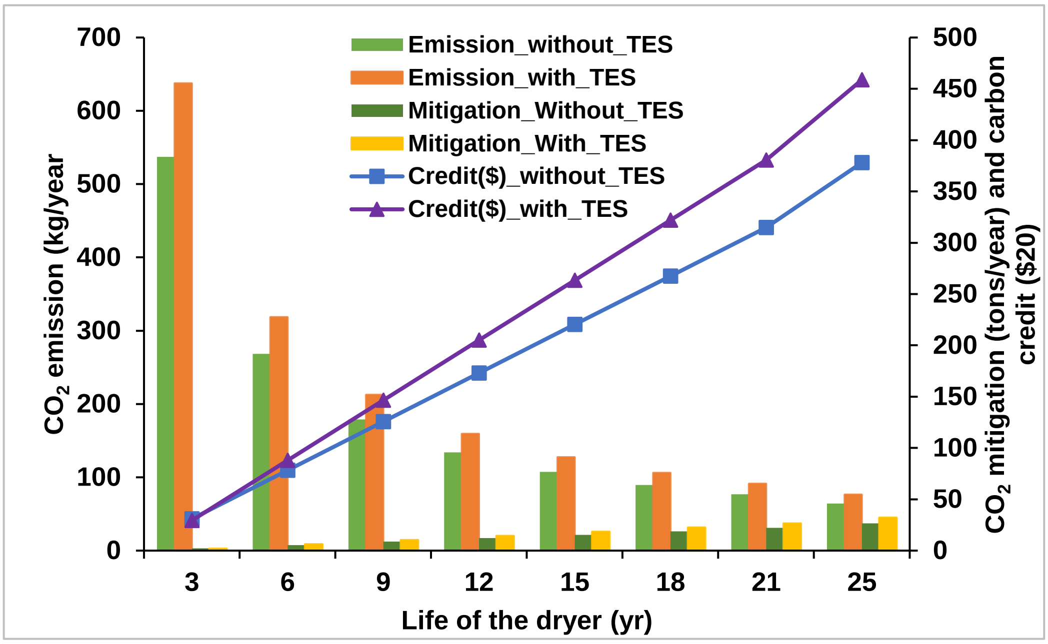


Fig. 4.39. Annual CO_2 emission, mitigation and credit of PITSD without and with TES during drying ivy gourd

4.5.2.3. Economic analysis

A PITSD without and with TES with a lifetime (L_d) of 25 years was constructed with a capital cost (C_T) of 10000 and 140000 INR ($ 1338 and 1873), respectively. The setups were fully loaded (1.25 kg × 4 trays = 5 kg) to analyze the economic importance of drying ivy gourd in a PITSD without and with TES and summarized in **Table 15**. Ivy gourd was dried from 15.32 (db) to 0.144 (db) in 18 and 16 h in the setups without and with TES, respectively. The total annual active sunshine hours was taken to be 2160 (9 months × 240 days). The prices of fresh and dried ivy gourd per kg were 60 and 150 INR, respectively. The yearly cost of the dryer (C_y) without and with TES setups was 3995.10 and 5995.65 INR, respectively. The C_y was higher for the setup with than without TES setup because of the costs incurred to modify with the TES (PCM, polycarbonate, Al, etc.). The annual drying cost per kg of ivy gourd was evaluated to be 5.33 and 3.99 INR for the setups without and with TES, respectively. The N of the setups without and with TES was estimated to be 2.16 and 1.49 years, respectively. The setup with TES reduced the payback period by 0.67 years which is a 31% improvement compared to the setup without TES.

Table 15. Economic parameters of drying ivy gourd in a PITSD setup without and with TES

Property	**Without TES**	**With TES**
Capital cost of dryer (C_T) (INR)	100000 INR ($ 1338)	140000 INR ($ 1873)
Total sunshine hours (h)	2160	2160
Potential of the dryer (kg)	5	5
Dried ivy gourd per year (kg)	675	1200
Annual cost (C_y) (INR)	3995.10 INR ($ 53.44)	5995.65 INR ($ 80.2)
Price of fresh ivy gourd (INR/kg)	60 INR ($ 0.8)	60 INR ($ 0.8)
Price of dried ivy gourd (INR/kg)	150 INR ($ 2)	150 INR ($ 2)
Annual drying cost (C_d) (INR/kg)	5.33 INR ($0.07)	3.99 INR ($0.05)
Payback period (N) (years)	2.16	1.49

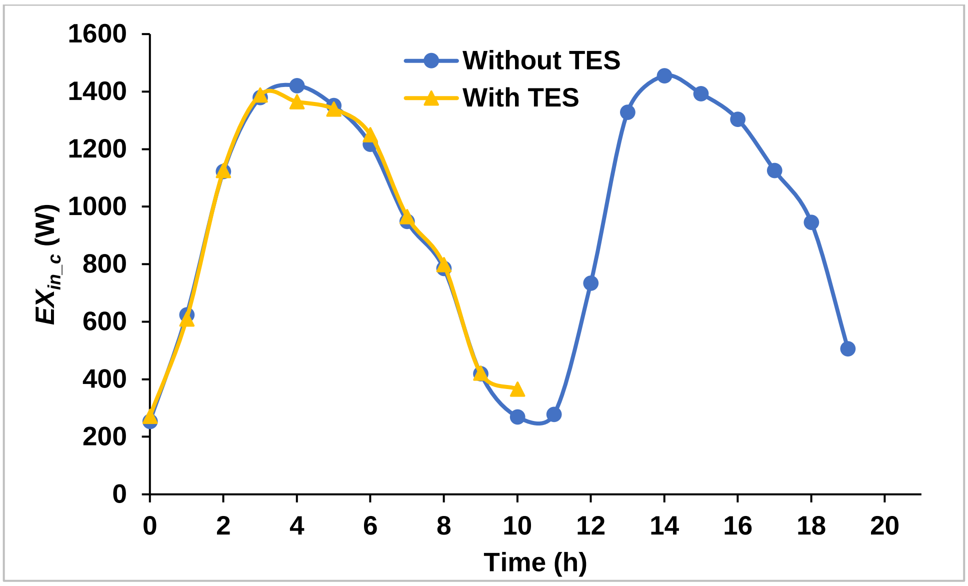
4.5.3. Evaluation of 3E parameters for drying pineapple in AITSD without and with TES

4.5.3.1. Exergy of collector

Collector's exergy inflow and outflow

Figure 4.40 (a) gives the EX_{in_c} with time during drying pineapple in AITSD without and with TES. It is dependent on the collector area, mass flow rate, solar intensity, and ambient air temperature [85, 155]. EX_{in_c} for without TES was assessed for one-day daylight drying hours, whereas EX_{in_c} for with TES was examined for two successive days' sunshine hours. The highest EX_{in_c} values were seen at midday when the sun intensity was supposed to be at its peak. The average EX_{in_c} for without and with TES were 967 and 901 W, respectively, while the evaluated values for the same were in the range of 254 – 1455 and 271 – 1389 W, respectively. In the same way, the $EX_{l\text{-}c}$ was calculated using temperature and radiation data collected during the drying experiment. Because of the plot's likeness to EX_{in_c}'s graph, it is not shown here. The average EX_{l_c} for without and with TES were 895 and 862 W, respectively, while the evaluated values for the same were in the range of 257 – 1388 and 255.1 - 1333.5 W, respectively.

(a)



(b)

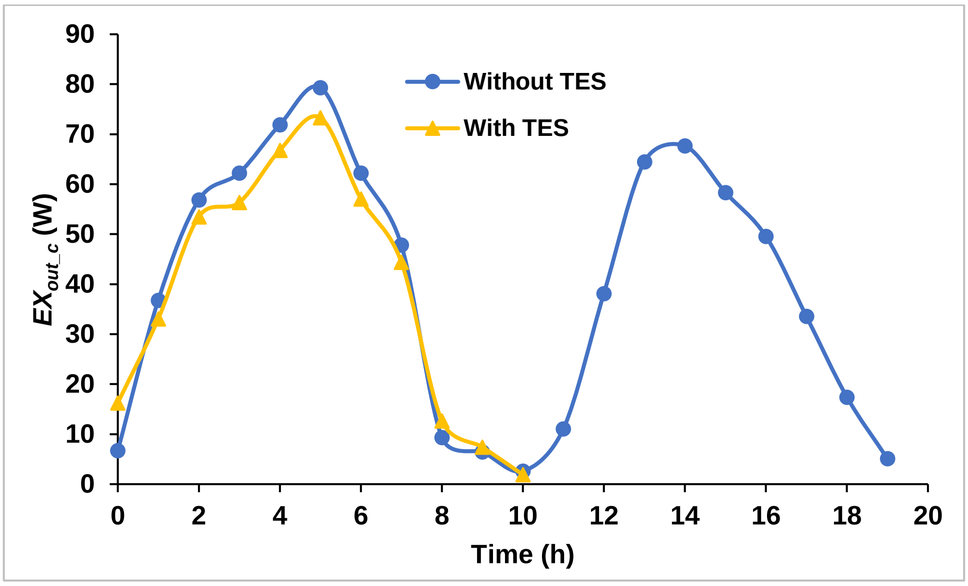


Fig. 4.40. Collector's exergy (a) inflow and (b) outflow for AITSD without and with TES

Figure 40 (b) depicts the instantaneous exergy outflow of the EX_{out_c} during drying pineapple in an AITSD integrated with TES and without TES. Similar to other exergy parameters of solar collectors, the maximum value was attained at midday. Since EX_{out_c} depends on the temperature of the ambient air, the collector outlet, and the inlet, after reaching the maximum value, the trend of variation rapidly increased before the rate of decline gradually accelerated with the solar intensity. There were slight differences in the values of EX_{out_c} between the two setups which might have been caused by variations in ambient air temperature.

Exergy efficiency of collector

The η_{EX_c} for AITSD without and with TES during drying pineapple has been evaluated and described in **Fig. 4.41**. The exergy inflow and outflow directly influence the exergy efficiency, thereby the characteristics with time variation tend to resemble **Fig. 4.40 (a)** and **(b)**. Moreover, solar radiation is one of the key influencing factors of EX_{in_c} which indirectly determines the exergy efficiency. Based on the corresponding values of 0.04-3.79 % and 0.513-3.97 %, the average η_{EX_c} for without and with TES was 2.33 and 2.12 %, respectively, which is almost at a similar range reported by Mugi and Chandramohan [152] (0.21 – 5.12%), Bhardwaj et al. [68] (0.81%).

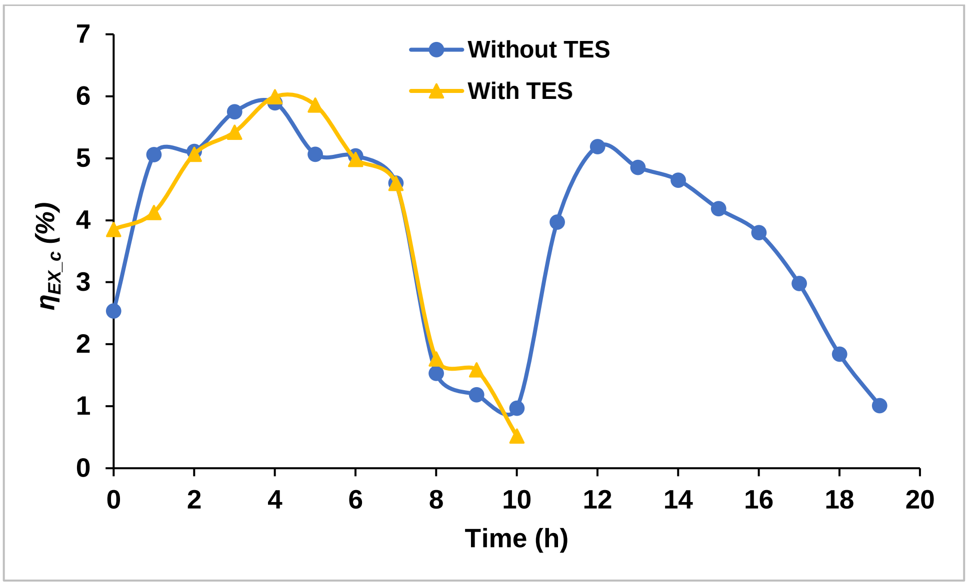


Fig. 4.41. Collector exergy efficiency for AITSD without and with TES during drying pineapple

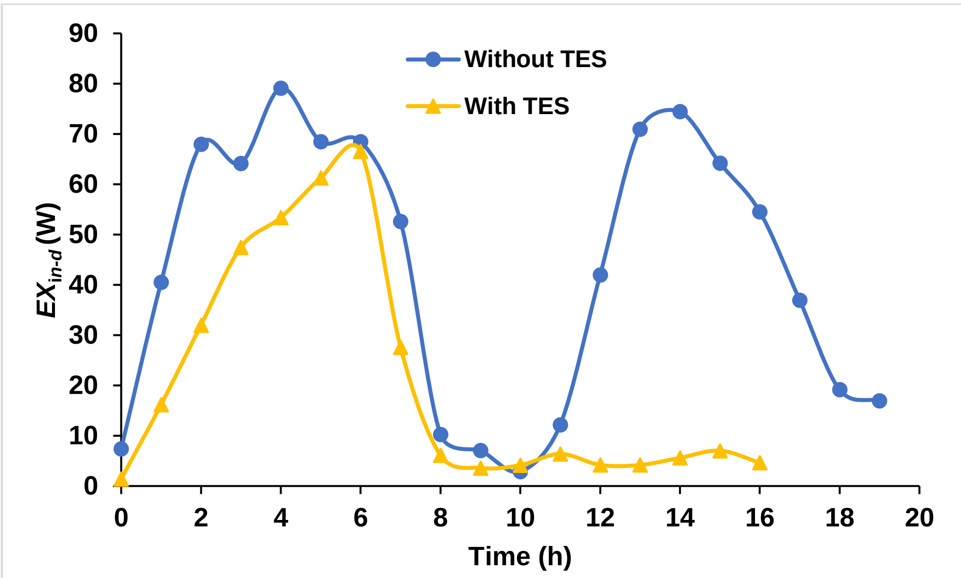
Estimation of the inflow (EX_{in_d}) and outflow (EX_{out_d}) of exergy for drying section

The instantaneous EX_{in_d} of AITSD without and with TES is displayed in **Fig. 4.42 (a)**. It was evaluated from the temperate data recorded during the experiment. As can be noticed from the mentioned **Fig. 4.42 (a)**, the EX_{in_d} was observed to vary similarly to the variation in solar radiation for both setups. For with TES, however, EX_{in_d} was almost constant after sunset because the TES unit sustains the temperature by discharging the thermal energy stored during sunshine hours. The average values of EX_{in_d} for without and with TES were 0.043 and 0.0207 kW, and their corresponding ranges were between 2.88 – 79.1 W and 1.41 – 66.5 W, respectively. Higher EX_{in_d} is noticed in without TES than with TES, which might be due to the EX_{in_d} being a function of the difference between its outlet and inlet temperatures, and the inlet temperature for without TES is less than with TES setup.

Figure 4.42 (b) represents the instantaneous EX_{out_d} for the drying experiments of pineapple in without and with TES. Similar to EX_{in_d}, EX_{out_d} depends on the temperature difference between the outlet and inlet of the drying section. EX_{in_d} is observed to be higher for without TES than with TES setup because of higher temperature inside without than with TES as TES charging and discharging process lower the temperature. The mean values of EX_{out_d} for without and with TES setups were 11.8 and 22.7 W, respectively. Its corresponding values estimated for the same were 0.459 – 31.9 W and 0.197 – 44.3 W, respectively. There was a 33.9% improvement in average EX_{out_d} in the drying section of with TES setup compared to without TES.

In general, as can be noticed from the **Figs. 4.42 (a)** and **(b)**, the variation of exergy inflow and outflow is alike with the variation of solar radiation implying that the exergy destruction for the drying section is dependent on the thermal energy (solar radiation).

(a)



(b)

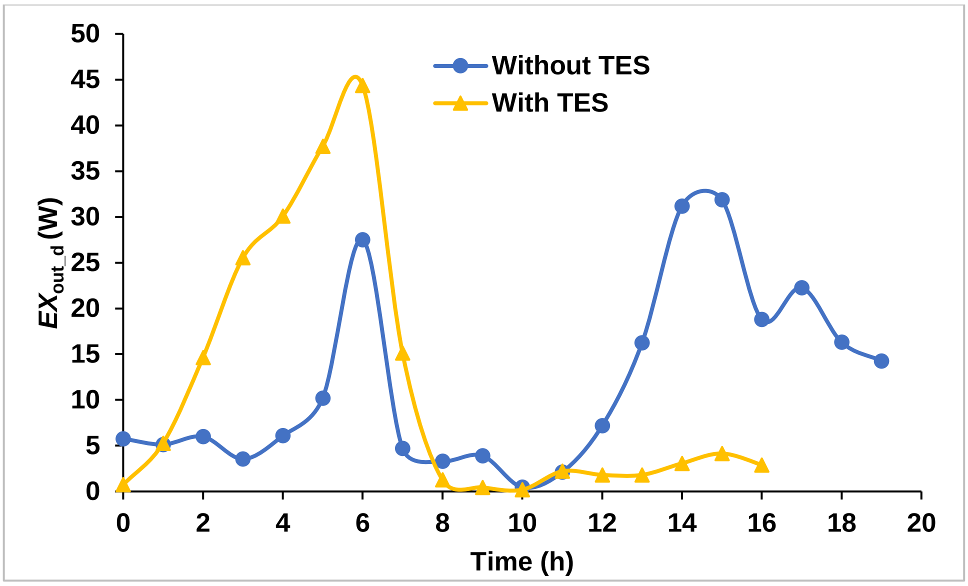
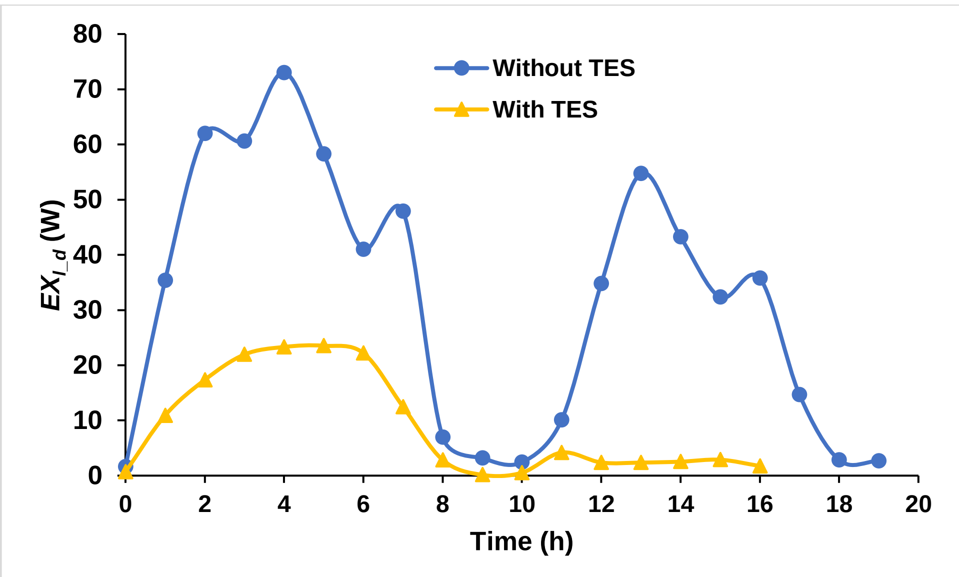


Fig. 4.42. Drying section's instantaneous exergy (a) inflow and (b) outflow for AITSD without and with TES

Exergy efficiency and loss of drying section

Figure 4.43 (a) represents the EX_{l_d} with time. From **Figure 4.43 (a)**, up to noon, EX_{l_d} appeared to be increasing, but afterward, it started declining. The mean value of EX_{l_d} for without and with TES were 31.2 and 8.94 W, respectively. The corresponding estimated values were in 1.61 – 73 W and 0.143 – 23.5 W, respectively. There was a 71.34% reduction of exergy loss in the drying section in with TES because of using the TES unit.

(a)



(b)

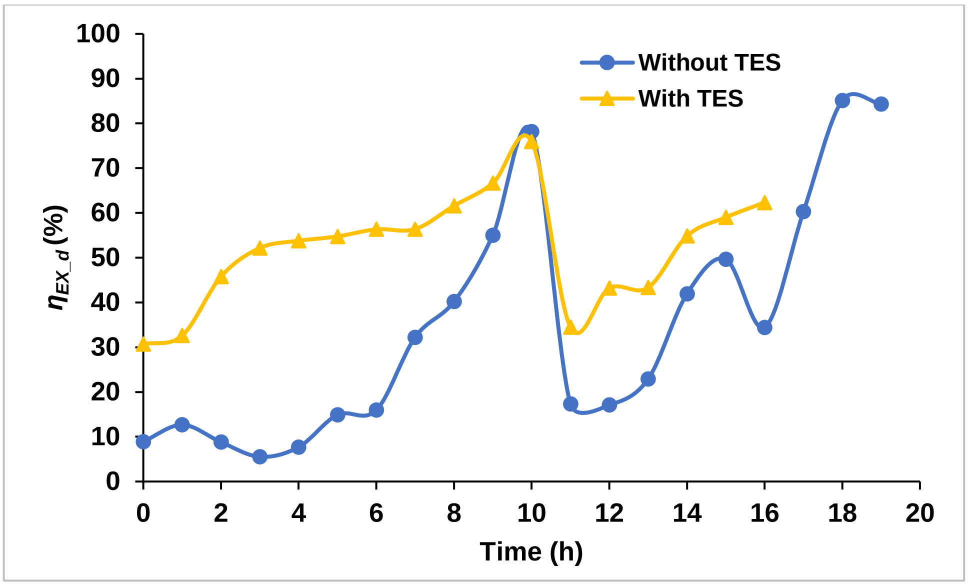


Fig. 4.43. The drying section's exergy (a) loss and (b) efficiency for AITSD without and with TES during drying pineapple

The η_{EX_d} for the drying experiment was evaluated from the temperature and mass data and described in **Fig. 4.43 (b)**. The η_{EX_d} is mainly dominated by the inflow and outflow of the exergy. The η_{EX_d} increases with time for both without and with TES setup. The mean value of η_{EX_d} for without and with TES was 34.66 and 57.07%, respectively, while the values were estimated as 5.53 – 85.13% and 32.59 – 75.98%, respectively. In with TES, there was a 64.66% improvement in exergy of the drying section compared to without TES. In the existing literature, Chowdhury et al. [42] reported 32 - 69% during drying jackfruit, Bhardwaj et al. [68] estimated 3.7 – 75.15% for medicinal herbs, Mugi et al. [139] evaluated in 2.26 - 51.85% during drying green chilli. The estimated data in the current analysis are in accord with the results reported by the scholars. Generally, from both Fig. (a), it is noticeable that exergy loss was directly varying with the thermal energy (solar radiation) supplied to the drying section. Its trends of variation with time is similar to those of exergy inflow and solar radiation with time. But, exergy efficiency unlike exergy loss, observed to be increasing with time unto the end of the drying experiment.

Exergy's sustainability indicators

The WER, IP, SI, and EIF are good sustainability indicators to design an efficient solar drying section. These indicators were estimated for figuring out the exergy output and loss of the drying section based on the exergy input. **Table 4.16** depicts the summary of estimated values of the exergy indicators. As can be seen from the mentioned **Table 4.16**, the average values of

WER, IP, SI, and EIF for without and with TES are 0.7274 and 0.6685%, 14.46, and 3.347 W, 1.573 and 2.232%, and 5.27 and 1.155%, respectively. Generally, WER, IP, and EIF were decreased by 8.1, 78.85, and 78.1%, respectively, for with TES compared to without TES. The ranges of the estimated values for all sustainability indicators are summered in **Table 4.16**. Mugi et al. [139] reported that IP was 4.22 W and WER was 0.438%. Mishra et al. [39] presented SI for a passive and active setups at 1.05 and 1.04%, respectively. These reports in the existing literature verify that the results of the current study are valid.

Table 4.16: Estimated exergy sustainability indicators of the AITSD without and with TES

Indicators	**Without TES**		**With TES**		**Variation (%)**	**Remark**
	Average	**Range**	**Average**	**Range**		
IP (W)	14.46	4.347– 18.78	3.347	1.674 - 4.832	76.85	Decrease
WER (%)	0.7274	0.2182-0.9447	0.6685	0.2402-0.003639	8.1	Decrease
SI (%)	1.573	1.0585-4.582	2.232	1.443-4.163	41.9	Increase
EIF (%)	5.27	0.2792-17.10	1.155	0.3161-2.668	78.1	Decrease

4.5.3.2. Environmental analysis

Embodied energy

Based on the mass of the elements and materials used in the construction of the AITSD, E_e was evaluated and described in **Table 4.17** for without and with TES setups. From **Table 4.17**, the E_e for without and with TES was 963.124 and 1408.22 kWh, respectively. Due to the extra mass of the TES unit, with TES setup has a higher E_e (445.1 kWh) than without TES setup.

Table 4.17. Embodied energy of AITSD without and with TES unit

Part	**Materials**	**Energy density** (kWh/kg) [19, 82, 146]	**Mass of component** (kg)		**Embodied energy, E_e** (kWh)	
			Without TES	**With TES**	**Without TES**	**With TES**
1	PCM (paraffin wax)	9.1	-	21	-	191.1

2	Aluminium (fins + tubes)	55.28	-	1.25	-	69.1
3	Polycarbonate	10.16	-	5	-	50.8
4	Glass	7.28	-	4	-	29.12
5	Thermocol	24.61	-	0.25	-	6.1525
6	Galvanized iron	9.64	24.4	34.25	235.22	330.17
7	Copper	19.61	1.8	1.8	35.298	35.298
8	Glass	7.28	0.9	0.9	6.552	6.552
9	Black paint	25.11	0.56	0.56	14.0616	14.0616
10	Wood	0.66	2	2	1.32	1.32
11	Plastic mesh	19.44	2	2	38.88	38.88
12	Glass wool	4.04	4.2	4.2	16.968	16.968
13	Thermocol	24.61	0.45	0.45	11.0745	11.0745
14	Mild steel +Trapezoidal duct	8.89	35.14	35.14	312.395	312.395
15	Steel	8.89	0.85	0.85	7.5565	7.5565
16	DC fan (plastics, copper wires)	19.4	0.35	0.35	6.79	6.79
		19.61	0.125	0.125	2.45125	2.45125
	Solar cell (kWh/m^2)	1130.6	0.26	0.26	293.956	293.956
Total			**60.3**	**102.05**	**963.124**	**1408.22**

Payback period for the energy

From the E_{AO} and E_e of an AITSD without and with TES assuming a lifetime of 35 years, the EPBP is evaluated. Alternatively, E_{AO} depends on the daily output of the solar dryer. Accordingly, the estimated values of E_{AO} for without and with TES were 640. 96 and 769.02 kWh/year, respectively. The corresponding EPBP for without and with TES was 1.503 and

1.831 years, respectively. Chauhan et al. [85] estimated EPBP of 2.35 years during bitter gourd in a greenhouse dryer. Mugi and Chandramohan [139] reported 2.15 years during drying green chilli in AITSD. Hence, the current study's results are agreeable from the existing literature.

CO_2 emission, mitigation and credit

Table 4.18 summarizes the estimated CO_2 emissions, mitigation, and credit calculated with a 35-year lifespan for AITSD without and with TES during drying pineapple. In a year, 2160 h (240 × 9) was considered for the estimation of the parameters. As shown in **Fig. 4.44**, CO_2 emission, mitigation, and carbon credit vary with the lifespan of the dryer. As implied in **Table 4.18**, the CO_2 emission for without and with TES setups is 56.19 and 39.03 kg/year, respectively. And the CO_2 mitigation for the same is 37.51 and 45.77 tons/year, respectively. Similarly, the carbon credit earned by without and with TES for the specified lifespan of the dryer is \$750.23 and \$915.43, respectively**.** There were 30.54%, 22.02%, and 26.82% annual improvements in CO_2 emission, mitigation, and credit, respectively, by using with TES instead of without TES.

For both setups, CO_2 emissions decreased, mitigation, and credit increased as the dryer's life increased. From the existing literature, Vijayan et al. [154] reported EPBP, CO_2 mitigation, and carbon credit for an ITSD were 2.21 years, 33.52 tons/year, and in the range of \$144.772 - \$579.087, respectively, for a lifetime of 35 years. Mishra et al. [39] presented 1.5 and 3.2 years of EPBP and economic payback period, respectively, for a greenhouse dryer with a lifespan of 10 years. Therefore, the present study's results are generally in agreement with those reported in the literature.

Table 4.18. Summary of estimated CO_2 emission, mitigation and credit for AITSD without and with TES

Type setup	**L_d (yr)** →	**4**	**8**	**12**	**16**	**24**	**28**	**32**	**35**
Without TES	CO_2 emission (kg/yr)	491.68	245.84	163.89	122.92	81.955	70.24	61.46	56.19

	CO_2 mitigation (ton/yr)	3.28	7.69	12.11	16.52	25.36	29.78	34.2	37.51
	Carbon credit($) 20$ base	65.36	153.73	242.1	330.47	507.21	595.58	683.95	750.23
With TES	CO_2 emission (kg/yr)	341.54	170.77	113.85	85.38	56.92	48.79	42.69	39.03
	CO_2 mitigation (ton/yr)	3.42	8.89	14.35	19.81	30.74	36.21	41.67	45.77
	Carbon credit($) 20$ base	68.42	177.71	287.00	396.29	614.87	724.17	833.46	915.43

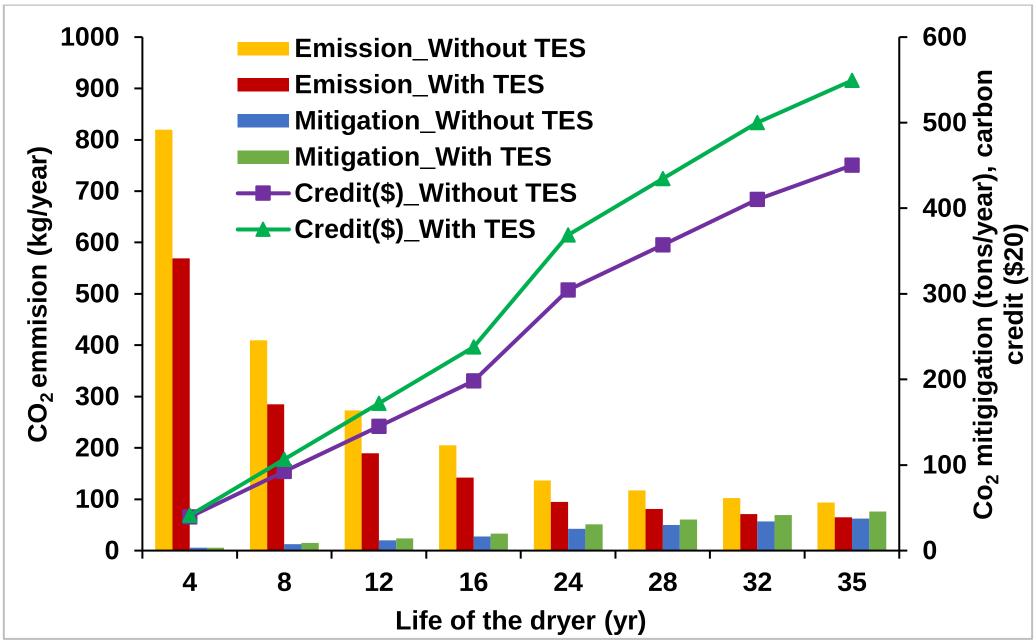


Fig. 4.44. Yearly emission, mitigation and credit of CO_2 for AITSD without and with TES

4.5.3.3 Economic analysis

The economic significance of an AITSD without and with TES has been evaluated by drying a 5 kg (1.25 kg × 4 trays) of pineapple slices by assuming the lifetime (L_d) of the dryer to be 35 years. It is summarized in **Table 4.19**. A total of 2610 active drying hours were taken for the estimation. For both without and with TES, the capital cost was 1, 15,000 INR ($ 1,517.09) and 1, 55,000 INR ($ 2,044.78), respectively. In India, the prices of fresh and dried pineapple were 120 INR ($1.9) and 350 INR ($ 4.6)/kg, respectively. In without TES setup, the cost of the dryer (C_y) was 4908 ($67.8), while in with TES, it was 6615.14 ($87.3). The C_y was higher for with TES than without because of the costs introduced to add TES structure (PCM, polycarbonate, Al, etc.) to the system. The yearly drying cost of the pineapple was estimated to be 7.12 INR ($0.093) and 4.9 INR ($0.05) for without and with TES, respectively. The *N* for the same was 1.41 and 0.93 years, respectively. Accordingly, as the TES unit is used, the economic payback period is reduced by 0.48 years (34.04%) compared to without the TES unit. In the existing literature [7], the N for a PITSD without and with TES was 1.51 and 1.04 years, respectively supporting the results of current study.

Table 4.19. Estimated economic impact indicators of drying pineapple in AITSD without and with TES

Property	**Without TES**	**With TES**
Capital cost of dryer (CT) (INR/$)	115000 INR ($ 1,517.09)	155000 INR ($ 2,044.78)
Total active hours (h)	2160	2160
Capacity of the dryer (kg)	5	5
Dried pineapple (kg /year)	680	1360
Annual cost (C_y) (INR/$)	4908 ($67.8)	6615.14 ($87.3)
Price of fresh pineapple (INR ($)/kg)	120 INR ($1.9)	120 INR ($ 1.9)
Price of dried pineapple (INR ($)/kg)	350 INR ($ 4.6)	350 INR ($ 4.6)
Annual drying cost (C_d) (INR ($)/kg)	7.12 ($0.093)	4.9 INR ($0.05)
Payback period (N) (yr)	1.41	0.93

4.5.4. Comparative discussion of overall 3E parameters

In this section, the comparative summary of 3E parameters evaluated for drying carrot in PITSD and AITSD without TES (**Table 4.20**) is discussed. And also the 3E parameters for drying of ivy gourd in a PITSD with and without TES is portrayed in **Table 4.21.** Similarly, for drying of pineapple in AITSD without and with TES are presented in **Table 4.22**. Based on the 3E analysis data, the following main comparison points addressed: The $\eta_{EX\text{-}c}$ is noticed to be higher (24.85%) for PITSD than AITSD during drying carrot. It is also higher (8.58%) for the PITSD without TES than with TES during drying ivy gourd. Similarly, 2.93% improvement in $\eta_{EX\text{-}c}$ was noticed for the AITSD without TES than with TES during pineapple drying. The $\eta_{EX\text{-}d}$ evaluated for drying of carrot is higher (34.87%) in AITSD than PITSD. It is also improved by 65.44% during drying ivy gourd in the PITSD with TES compared to without TES. Similarly, the AITSD showed a 64.66% increase in $\eta_{EX\text{-}d}$ by using TES during drying pineapple. Exergy stability indicators like WER, IP, SI, and EIF were significantly improved by applying active mode provision. They also were improved by applying TES in both PITSD (ivy gourd) and AITSD (pineapple) compared with their respective without TES setups.

The EPBP was longer by 0.45 years for AITSD than PITSD during drying carrot. And also it was 0.47 years longer for the with TES than without TES setup of PITSD in drying ivy gourd. Similarly, during pineapple drying, the AITSD support with TES took 0.33 more years than without TES to pay back the energy. The extra mass of active mode provision and the TES were the reason for the longer EPBPs. The CO_2 emission was not improved in AITSD without TES and PITSD with TES. But there was improvement by using AITSD supported with TES compared to without TES setup. Carbon migration and credit were improved by using active mode provision and TES.

The *N* was improved by 0.36 years for drying carrot in AITSD compared to PITSD. It was also enhanced by 0.67 years for drying of ivy gourd in PITSD supported with TES compared to without TES. Similarly, during drying pineapple, the AITSD supported with TES improved the N by 0.48 years compared to without TES.

Overall, AITSD performed better than PITSD in almost every 3E parameters. PITSD and AITSD supported with TES showed better performance than their respective without TES setups in 3E parameters. Accordingly, 3E analysis indicates that using AITSD would improve the overall performance of the drying system.

Table 4.20. Summary of 3E parameters for carrot drying in PITSD and AITSD without TES

Parameter	**Passive**	**Active**	**Difference (%)**
EX_{in_c} (W)	1004.87	931.65	**7.86**
EX_{out_c}(W)	35.49	24.92	**29.78**
η_{EX_c} (%)	3.62	2.72	**24.86**

EX_{in_d} (W)	38.67	17.47	**54.82**
EX_{out_d} (W)	16.21	10.27	**55.58**
η_{EX_d} (%)	43.3	58.4	**34.87**
EPBP (yr)	1.33	1.78	**33.83**
N (yr)	1.02	0.622	**27.83**

Table 4.21. Summary of 3E parameters for ivy gourd drying in PITSD without and with TES

Parameter	**without**	**with**	**Difference (%)**
EX_{in_c} (W)	974.94	877.46	**10**
EX_{out_c}(W)	27.6	25.12	**8.99**
η_{EX_c} (%)	2.33	2.13	**8.58**
EX_{in_d} (W)	27.34	17.01	**37.78**
EX_{out_d} (W)	7.46	10.4	**39.41**
η_{EX_d} (%)	31.14	51.52	**65.44**
EPBP (yr)	1.04	1.51	**45.2**
N (yr)	2.16	1.49	**31.02**

Table 4.22. Summary of 3E parameters for pineapple drying in AITSD without and with TES

Parameter	**without**	**With**	**Difference (%)**
EX_{in_c} (W)	936.6	900.1	**3.9**
EX_{out_c}(W)	42.63	38.44	**9.82**
η_{EX_c} (%)	4.1	3.98	**2.93**
EX_{in_d} (W)	43.01	20.69	**42.53**
EX_{out_d} (W)	11.84	11.25	**4.98**
η_{EX_d} (%)	34.66	57.07	**64.66**
EPBP (yr)	1.503	1.831	**21.82**
N (yr)	1.41	0.93	**34.04**

4.6. Comparative analysis of overall parameters of the PITSD and AITSD

In this particular section, the overall drying performance parameters and drying kinetics of ivy gourd, pineapple and carrot are comparatively assessed during drying in passive and active

ITSDs and summarized in **Tables 4.23**, **4.24**, and **4.25**, respectively. And also, the exergy, environmental and economic parameters for passive and active ITSDs were comparatively evaluated and presented in **Tables 4.26** (carrot drying), **4.27** (ivy gourd drying), and **4.28** (pineapple drying). Accordingly, from the overall analysis, the following main points are summarized.

The drying performance parameters were improved over the range of 3.44 – 78.85% in AITSD compared to PITSD. The η_c was improved by 23.4 and 11.9% by using AITSD without and with TES during drying ivy gourd compared to PITSD. The same for drying of pineapple was 12.67 and 16.52%; for drying of carrot was 20.9 and 13.6%, respectively. Similarly, the η_d was improved by 27.45 and 12.59% in AITSD without and with TES during drying ivy gourd, respectively. And also, 10.01 and 22.7% enhancement of η_d was noticed in AITSD without and with TES, respectively, during drying of pineapple. Similarly, the same for carrot drying was 27.33 and 27.93% in AITSD compared to PITSD. Generally, there were improvements in all performances parameters by using AITSD during the drying experiments.

The improvement in percentage of the drying kinetics were recorded in the range of 7.63 - 67.58% by using AITSD compared to AITSD. The D_e, h, *and* h_m were improved in AITSD without and with TES. AITSD also improved SEC and SMER during all the three samples. Similarly, there was significant improvement in E_a by using active mode provisions. The logarithmic correlations were noticed between D_e, h and h_m vs MC, and all of them were increased with the decrease of MC. Drying time was reduced by using active mode provisions (2 h for each during drying ivy gourd and pineapple, and 3 h during drying carrot). Moreover, integrating TES helped the drying process complete in one day with only one day radiation.

Almost all the exergy parameters considered for the analysis except collector exergy parameters, were improved in AITSD compared to PITSD. The exergy indicating parameters for the drying section were higher for AITSD compared to PITSD. They were also higher for the passive and active setups with TES compared to without TES setups. The environmental impact parameters except EPBP and CO_2 emission were noticed to be improved by using AITSD compared PITSD. The economic importance indicators showed improvement in the range of 31.3 - 39.02% by using AITSD compared to PITSD. The N was improved by 0.36 years for drying carrot in AITSD compared to PITSD. It was also enhanced by 0.67 years for drying of ivy gourd in PITSD supported with TES compared to without TES. Similarly, during drying pineapple, the AITSD supported with TES improved the *N* by 0.48 years compared to without TES.

Comparatively, AITSD showed good improvement in both drying performance parameters and drying kinetics during drying of all the samples (ivy gourd, pineapple, and carrot). Supporting the setups with TES enhanced the performance parameters compared to their respective without TES setups during drying all the three samples. Similarly, AITSD performed better than PITSD in almost every 3E parameters. PITSD and AITSD supported with TES showed better performance than their respective without TES setups in 3E parameters.

Table 4.23. Summary of overall parameters for ivy gourd drying in PITSD and AITSD

Parameters	**Without TES**			**With TES**		
	Passive	**Active**	**Difference (%)**	**Passive**	**Active**	**Difference (%)**
η_c (%)	62.56	77.2	**23.4**	62.7	69.87	**11.9**
η_d (%)	6.62	7.8	**27.45**	13.15	15.2	**12.59**
D_e (m^2/s)	7.06×10^{-9}	8.35×10^{-9}	**19.01**	8.06×10^{-9}	10.00×10^{-9}	**24.07**
h_m (m/s)	3.3×10^{-3}	4.3×10^{-3}	**28.05**	0.0041	0.0055	**34.14**
h (W/m^2 K)	3.85	4.93	**30.3**	4.7	6.28	**33.62**
E_a (kJ/mol)	36.85	35.54	**10.81**	39.35	36.35	**7.63**
SEC (kWh/kg)	1.549	1.144	**26.15**	0.265	0.228	**13.96**
SMER (kg/kWh)	0.646	0.875	**35.45**	3.78	4.380	**15.87**
Q_a (W)	776.66	997.76	**28.47**	735.9	761.2	**3.44**
T_{co} max (°C)	66	62	**6.06**	64.5	61	**5.43**
T_{co} (°C)	51.7	48.5	**6.19**	45.71	42.59	**6.83**
DR_a (kg/h)	0.85	1.019	**19.89**	0.83	0.95	**15**
MC (db)	initial	final		initial	final	
	15.56	0.144		15.56	0.144	
Total time (h)	16	13	**3 h**	16	14	**2 h**

Table 4.24. Summary of overall parameters for pineapple drying in PITSD and AITSD

Parameters	Without TES			With TES		
	Passive	Active	Difference (%)	Passive	Active	Difference (%)
η_c (%)	60.72	68.41	**12.67**	58.18	67.79	**16.52**
η_d (%)	6.92	7.61	**10.01**	9.7	11.9	**22.7**
D_e (m^2/s)	7.306×10^{-9}	8.51×10^{-9}	**16.5**	5.25 × 10-9	5.97×10^{-9}	**12.4**
h_m (m/s)	8.25×10^{-3}	10.6×10^{-3}	**28.49**	4.89×10^{-3}	5.76×10^{-3}	**8.81**
h (W/m^2 K)	9.52	12.2	**28.15**	5.6	6.47	**14.92**
E_a (kJ/mol)	34.76	31.83	**8.19**	42.72	38.34	**10.23**
SEC (kWh/kg)	4.84	1.57	**67.52**	0.322	0.273	**15**
SMER (kg/kWh)	0.207	0.635	**75.85**	3.1	3.67	**18.39**
Q_a (W)	704.25	789.38	**12.1**	813	902	**10.95**
T_{co} max (°C)	81	69	**14.81**	66.5	63	**5.26**
T_{co} (°C)	62.9	55.1	**12.4**	44.9	43.4	**3.34**
DR_a (kg/h)	0.375	0.447	**19.2**	0.408	0.45	**10.3**
MC (db)	initial	final		initial	final	
	7.91	0.417		7.91	0.417	
Total time (h)	14	12	**2 h**	16	14	**2 h**

Table 4.25. Summary of overall parameters for carrot drying in PITSD and AITSD

Parameters	Without TES			With TES		
	Passive	Active	Difference (%)	Passive	Active	Difference (%)
η_c (%)	56.84	68.74	**20.94**	59.7	67.8	**13.6**
η_d (%)	7.5	9.55	**27.33**	11.1	14.2	**27.93**
D_e (m^2/s)	6.7×10^{-9}	7.35×10^{-9}	**9.7**	7.2×10^{-9}	8.0×10^{-9}	**11.1**
h_m (m/s)	5.5×10^{-3}	6.5×10^{-3}	**18.18**	6.2×10^{-3}	7.1×10^{-3}	**14.52**
h (W/m^2 K)	6.35	7.25	**14.72**	7.1	7.9	**11.3**
E_a (kJ/mol)	42.71	37.85	**12.84**	45.1	39.6	**12.2**
SEC (kWh/kg)	4.72	3.2	**32.2**	0.276	0.219	**20.7**

SMER (kg/kWh)	0.202	0.302	**47.1**	3.6	4.6	**27.8**
Q_a (W)	705.64	789.55	**11.89**	722	807.4	**11.82**
T_{co} max (°C)	75	66	**12**	71	65	**8.45**
T_{co} (°C)	61.2	53.1	**13.24**	45.7	44.3	**6.55**
DR_a (kg/h)	0.502	0.561	**11.75**	0.49	0.53	**8.16**
MC (db)	initial	final		initial	final	
	9.13	0.448		9.13	0.448	
Total time (h)	16	13	**3 h**	15	12	**3 h**

Table 4.26. Summary of 3E parameters for carrot drying in PITSD and AITSD

Parameters	**Without TES**		
	Passive	**Active**	**Difference (%)**
$EX_{in\text{-}c}$ (W)	1004.87	931.65	7.86
$EX_{out\text{-}c}$ (W)	35.49	24.92	29.78
$EX_{l\text{-}c}$ (W)	969.38	906.73	6.46
$\eta_{EX\text{-}c}$ (%)	6.12	3.62	40.85
$EX_{in\text{-}d}$ (W)	38.67	17.47	54.82
$EX_{out\text{-}d}$ (W)	16.21	10.27	55.58
$EX_{l\text{-}d}$ (W)	22.47	7.2	83.37
$\eta_{EX\text{-}d}$ (%)	43.3	58.4	34.87
IP (W)	12.74	3	76.45
WER (%)	0.57	0.42	26.32
SI (%)	2.0	3.75	87.5
EIF (%)	2.93	1.67	43.0
EPBP (yr)	1.33	1.78	33.83
N (yr)	1.02	0.622	39.02

Table 4.27. Summary of 3E parameters for ivy gourd drying in PITSD without and with TES

Parameters	**Passive (ivy gourd)**		
	Without	**With**	**Difference (%)**
$Ex_{in\text{-}c}$ (W)	974.94	887.47	**8.97**

Ex_{out-c} (W)	27.6	25.12	**8.99**
Ex_{l-c} (W)	934.85	852.35	**8.82**
67	2.33	2.13	**9.87**
Ex_{in-d} (W)	23.34	17.01	**27.12**
Ex_{out-d} (W)	7.43	10.04	**35.13**
Ex_{l-d} (W)	19.87	6.97	**64.82**
6	31.14	51.52	**65.46**
IP (W)	13.69	3.380	**71.44**
WER (%)	0.6886	0.4848	**29.6**
SI (%)	2.1	2.321	**10.52**
EIF (%)	7.007	1.811	**74.15**
EPBP (yr)	1.04	1.51	**45.2**
N (yr)	2.16	1.49	**31.3**

Table 4.28. Summary of 3E parameters for pineapple drying in AITSD without and with TES

Parameters	**Active (pineapple)**		
	Without	**With**	Difference (%)
Ex_{in-c} (W)	936.6	900.1	**3.9**
Ex_{out-c} (W)	42.63	38.44	**9.82**
Ex_{l-c} (W)	894.59	862.06	**3.53**
η_{EX-c} (%)	4.1	3.98	**2.93**
Ex_{in-d} (W)	43.01	20.69	**42.53**
Ex_{out-d} (W)	11.84	11.25	**4.98**
Ex_{l-d} (W)	31.17	8.94	**71.32**
η_{EX-d} (%)	34.66	57.07	**64.66**
IP (W)	0.01446	0.003347	**76.85**
WER (%)	0.7274	0.6685	**8.1**
SI (%)	1.573	2.232	**41.9**
EIF (%)	5.27	1.155	**78.1**
EPBP (yr)	1.503	1.831	21.82
N (yr)	1.41	0.93	34.04

4.7. Summary of uncertainty results

The average values of evaluated uncertainties for the experimental and estimated variables by using root-sum square method [144] is summarized in **Table 4.29**.

Table 4.29. Summary of estimated uncertainties

Parameter	Uncertainty
Air inlet velocity	± 0.031 m/s
Exergy input, output and loss of collector	± 22.1, ± 0.71 and ± 17.2 W
Exergy efficiency of collector	± 0.075%
Exergy efficiency of drying section	± 1.26% and
Exergy inflow, output and loss of drying cabinet	± 0.75, ± 0.28 and ± 0.41 W
Temperature	± 1 ^oC
Mass	± 0.0002 g
Solar radiation	± 10 W/m^2
Sustainability index	± 0.395
Waste energy ratio	± 0.0118
Environmental impact factor	± 0.15 W
Improvement potential	± 0.37 W
Actual heat supply	±23.41 W
Collector efficiency	±1.379%
Drying efficiency	±0.82%
Moisture content	± 0.0411 (db)
Activation energy	±0.076 kJ/mol
Heat transfer coefficient	±0.031 W/m^2K
Moisture diffusion coefficient	±1.56%
Mass transfer coefficient	$\pm 3.2\times10^{-5}$ m/s
Moisture ratio	±0.021
Relative humidity	± 2%

Chapter 5

Conclusions

Chapter 5

5. Conclusions

A series of solar drying experiments of agriproducts (ivy gourd, pineapple, and carrot) were performed to evaluate the performances of passive indirect type solar dryer (PITSD) (without and with TES) and active indirect solar dryer (AITSD) (without and with TES). Active mode provisions were developed in the existing PITSD dryer so that mass flow rate of the drying air was increased. The performance parameters of the dryers and the drying kinetics of the samples have been estimated for both PITSD (without and with TES) and AITSD (without and with TES). And also the exergy, environmental, and economic (3E) parameters for the systems were investigated. Moreover, the overall performance parameters of the setups have been comprehensively evaluated and compared.

The mass variation and temperature data have been recorded from the experiments. The performance parameters such as temperature distributions, actual heat supply (Q_a), collector efficiency (η_c), drying efficiency (η_d), specific energy consumption (SEC), and specific moisture extraction rate (SMER) were investigated. The drying kinetics namely moisture content (MC), moisture ratio (MR), drying rate (DR), moisture diffusion, heat transfer, mass transfer coefficients (D_e, h and h_m), and activation energy (E_a) were estimated. Exergy parameters of solar collector and drying section have been addressed. The exergy stability indicators also estimated. The environmental impact indicators such as embodied energy (E_e), energy payback period (EPBP), CO_2 emission, mitigation and credit have been evaluated. The economic analysis was performed to investigate the economic payback period (N).

Finally, the overall performance parameters of the dryers, the drying kinetics of the samples, and the 3E parameters of the systems have been comprehensively and comparatively analyzed and described. Based on the results of the study, the following main conclusions are presented in the subsequent sections:

5.1. Development of active mode provisions

By using a trapezoidal shaped duct integrated by 3 CPU fans powered by 3 PV solar panels, an active mode provision was developed and tailored on the air inlet of the existing PITSD so as to promote the mass flow rate of the drying air. Accordingly:

- The developed setup was easily constructed from the available materials with a minimum cost to perform the active mode experiments.
- Notably, the structure of the trapezoidal duct can be flexibly manufactured in accord with the design of the host setup (PITSD).
- It didn't take much energy to install, and was easy to perform suitably all the active drying experiments (all the samples dried for this study).
- It is also easy to operate so that any unskilled man can perform a drying of agriproducts.

5.2. Performance parameters of PITSD and AITSD without TES

After the tests were pereformed in the PITSD, the AITSD was facilitated by fitting a trapezoidal duct with three fans aided by PV panels. The major findings on the performance parmeters were inferred:

- The average collector outlet temperature (T_{co}) of PITSD and AITSD was 51.7 & 48.5 °C, 62.9 & 55.3 °C, 61.2 & 53.1 °C during drying of ivy gourd, pineapple, and carrot, respectively. Higher temperature was noticed in PITSD than AITSD.
- The Qa was noticed to be improved by 28.47, 12.1, and 11.89% during drying ivy gourd, pineapple, and carrot in AITSD compared to PITSD, respectively. The higher mass flow rate in AITSD would be the reason for the improvements.
- The average η_c was improved by 23.4, 12.67, and 20.94% during drying ivy gourd, pineapple and carrot in AITSD, respectively. Similarly, there were 27.45, 10.01, 27.33% increments of η_d in AITSD for the same. AITSD was better in η_c and η_d than PITSD during drying all the three samples.
- The SEC for drying ivy gourd, pineapple, and carrot were minimized by 26.15, 67.52, and 32.2%, respectively in AITSD compared to PITSD. Similarly, the SMER for the same was improved by 35.45, 75.85, and 47.1%, respectively. Both SEC and SMER were noticeably improved by using AITSD.

5.3. Drying kinetics in PITSD and AITSD without TES

By evaluating the mass variation and temperature data recorded during drying experiments of ivy gourd, pineapple, and carrot in PITSD and AITSD, the drying kinetics were estimated thereby the following main conclusion remarks were drawn:

- The MC of the ivy gourd was decreased from 15.32 to 0.144 (db) and it took 16 and 13 h in PITSD and AITSD, respectively. And also, for the pineapple the MC was reduced from 7.91 to 0.417 (db) in 14 and 16 h, respectively in the same setups. Similarly, carrot was dried from 9.13 to 0.448 (db) within 16 and 13 h in PITSD and AITSD, respectively. There were 3, 2, and 3 h reductions in drying time of ivy gourd, pineapple, and carrot, respectively by using AITSD.

- The average DR of ivy gourd, pineapple, and carrot in PITSD and AITSD were 0.85 & 1.019, 0.375 & 0.447, and 0.502 & 0.561 kg/h, respectively. Faster DR was observed in AITSD compared to PITSD.
- The De, h, and hm of ivy gourd were improved by 19.01, 30.3, and 28.05% in AITSD, respectively. The same for the pineapple was improved by 16.5, 28.15, and 28.49%, respectively. Similarly, there were 9.7, 14.72, and 18.18% improvements in De, h, and hm during drying carrot in the AITSD compared to PITSD.
- The Ea noticed to be reduced by 10.81, 8.19, and 12.84% during drying ivy gourd, pineapple, and carrot, respectively in AITSD compared to PITSD.
- The De, h, and hm were increased with the decrease of MC in a logarithmic tends; and the three parameters were increased with time.

5.4. Performance parameters and drying kinetics of PITSD and AITSD with TES

After the exepriments in the PITSD and AITSD were completed, a system using PCM as theraml energy storage (TES) was integrated inside the drying section just below the first tray. The following main findings on the performance parmeters and drying kinetics were inferred:

- Supposedly at a nearly equivalent solar radiations, the Tco for PITSD and AITSD were 45.17 & 42.59 ºC, 44.9 & 43.4 ºC, and 45.7 & 44.3 ºC for ivy gourd, pineapple, and carrot drying days. AITSD had less Tco than PITSD supported with TES. And again there was considerable improvements on the average Q_a in the AITSD compared to PITSD.
- The ηc was improved by 11.9, 16.52, and 13.6% during drying ivy gourd, pineapple, and carrot in AITSD compared to PITSD with TES setups. Similarly, the η_d was enhanced by 12.59, 22.7, and 27.93% for drying of the same, respectively.
- The D_e, h, and h_m were also considerably improved by using AITSD supported with TES. The E_a and SEC were also reduced for drying all the three samples in the AITSD. The SMER was increased by 15.87, 15, and 27.8% during drying ivy gourd, pineapple, and carrot in AITSD compared to PITSD.

- AITSD had higher (by 15, 10.3, and 8.16% during drying ivy gourd, pineapple, and carrot, respectively) DR than PITSD.
- Additionally, the drying time of ivy gourd, pineapple, and carrot was shorten by 2, 2, and 3 h, respectively in AITSD with TES compared to PITSD with TES. The TES also helped the drying experiments to last more than 6 h continuously after the sunset.
- The D_e, h, and h_m were negatively related with MC in a logarithmic functions; but positively correlated with time.

5.5. Exergy, environmental, and economic (3E) parameters

The 3E analysis have been performed for a PITSD and AITSD without TES (carrot drying), PITSD without TES and supported with TES (ivy gourd drying), and AITSD without and with TES (pineapple drying). A comparative assessments of the performances of the three respective pair setups were made; the following concluding remarks were inferred.

5.5.1. PITSD and AITSD without TES (carrot drying)

- The exergy inflow (EX_{in_c}), outflow (EX_{out_c}), and loss (EX_{l_c}) of the collector and drying section (EX_{in_d}, EX_{out_d}, and EX_{l_d}) were noticed to be higher for PITSD than AITSD without TES during drying carrot. Similarly, the exergy efficiency of collector (η_{EX_c}) was reduced by 40.85%; and the exergy efficiency of the drying section (η_{EX_d}) was improved by 34.87% by using AITSD. Moreover, the exergy stability indicators like waste exergy ratio (WER), improvement potential (IP), stability index (SI), and environmental impact factor (EIF) were also showed improvements in AITSD compared to PITSD.
- The environmental impact indicators like EPBP and CO_2 emission was higher for PITSD than AITSD while carbon mitigation and credit were better for AITSD than PITSD. The EPBP was 1.33 and 1.78 years for PITSD and AITSD, respectively.
- The N was 1.02 and 0.622 for PITSD and AITSD, respectively. There was 39.02% (0.4 years) improvement in N by using AITSD.

5.5.2. PITSD without and with TES (ivy gourd drying)

- During drying ivy gourd in PITSD without and with TES, the EX_{in_c}, EX_{out_c}, EX_{l_c}, η_{EX_c}, and EX_{in_d} were noticed to be higher for without than with TES setup. The EX_{out_d} and EX_{l_d} were improved by 35.15 & 64.82%, respectively in with TES setup compared to without TES. And again, η_{EX_d} was enhanced by 65.46% by applying TES in PITSD. Moreover, there were noticeable improvements in WER, IP, SI, and EIF in PITSD with TES compared to the without TES setup.

- There were higher EPBP and CO_2 emission in with TES setup because of higher embodied energy (E_e) due to the mass of materials for constructing TES; while carbon mitigation and credit were better for with than the without TES setup. The EPBP was 1.04 and 1.51 years for without and with TES setups, respectively.
- The N was improved by 39.02% (0.67 years) by using TES in PITSD where the estimated values of N were 2.16 and 1.49 for without and with TES, respectively.

5.5.3. AITSD without and with TES (pineapple drying)

- Similar to PITSD mentioned the preceding section, during drying pineapple in AITSD without and with TES, the EX_{in_c}, EX_{out_c}, EX_{l_c}, η_{EX_c}, EX_{in_d}, EX_{out_d}, and EX_{l_d} were higher for without than the with TES setup. Similarly, the η_{EX_d} was improved by 64.66% in with TES compared to without TES. Furthermore, the WER, IP, SI, and EIF were recognized to be improved in the with TES setup than without TES.
- There were improvements in CO_2 emission, carbon mitigation, and credit in the with TES setup than without TES. The EPBP was 1.5 and 1.83 years for without and with TES setups, respectively. The higher E_e due to mass of materials for constructing TES was reason for higher EPBP in the with TES setup.
- AITSD with TES showed an improvement of 34.04% (0.48 years) in N, where its values were 1.41 and 0.93 years for the without and with TES setups, respectively.

5.6. Comprehensive and comparative analysis of the overall performances of PITSD and AITSD

- The drying performance parameters were improved over the range of 3.44 – 78.85% in AITSD compared to PITSD. Generally, there were improvements in all performances parameters by using AITSD during the drying experiments.
- The improvement in percentage of the drying kinetics were recorded in the range of 7.63 - 67.58% by using AITSD compared to AITSD. Drying time was reduced by using active mode provisions. Moreover, integrating TES helped the drying process complete in one day with only one day radiation.

- Almost all the exergy parameters considered for the analysis except collector exergy parameters, were improved in AITSD compared to PITSD. The same was true for the passive and active setups with TES compered to without TES setups.
- The environmental impact parameters except EPBP and CO_2 emission were noticed to be improved by using AITSD compared to PITSD.
- The economic importance indicators showed improvements in the range of 31.3 - 39.02% by using AITSD compared to PITSD. Adding TES in PITSD and AITSD also showed improvements in the economic parameters.
- The three samples of this study (ivy gourd, pineapple, and carrot) showed different drying characteristics. Because the drying nature of the agriproducts vary depending on morphology, shape, the nature of the product, and other properties.

Generally, ITSD can easily be fabricated with minimum cost and can be used to dry all type of agricultural food products. The AITSD performed well in drying performance compared to PITSD. Similarly, PITSD underperformed in relation to drying kinetics. The velocity of drying in AITSD played a greater role in improving all drying performance parameters, drying kinetics and 3E parameters. TES in an ITSD helped the drying process to be completed continuously within a day. AITSD was found to be superior to PITSD on 3E parameters evaluated in this study. The temperature of drying air played main role in drying process. Because all the parameters are directly or indirectly influenced by the temperature of the drying air.

Overall, AITSD showed better improvements in all drying performance parameters, drying kinetics during drying all the samples (ivy gourd, pineapple, and carrot), and 3E parameters. And also, PITSD and AITSD supported with TES showed better performances in 3E parameters compared to their corresponding without TES setups. Hence, in this study the AITSD showed a promising results.

Future scope of work

- Further study is required to optimize the design parameters and materials required for the construction of setup so as to make the system more effective.
- ITSD in general and AITSD setups in particular would be so helpful for the less privileged farmers like Africa (Ethiopia) if properly utilized.
- It would be highly recommend to numerically optimize the drying performance parameters, the drying kinetics, the mass of drying objects, the volume and type of TES

materials, and other necessary parameters depending on the geography and atmospheric condition of a specific application area. It would help to validate the experimental results and predicting the parameters and operating conditions for large scale drying process.

- Further investigations at large scale with different preconditions would improve the results accuracy and reliability.
- The results of this study would be a base for further researchers and policy implementers.

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Publications

1. **M. C. Gilago** and V. P. Chandramohan, "Performance evaluation of natural and forced convection indirect type solar dryers during drying ivy gourd: An experimental study," *Renewable Energy*, vol. 182, 2021. https://doi.org/10.1016/j.renene.2021.11.038. (**Elsevier, SCI, IF = 8.634**)
2. **M. C. Gilago**, V.P. Chandramohan, "Effect of phase change materials on the performance of natural convection indirect type solar dryer during drying ivy gourd," *Heat Transfer Engineering*, vol. 44, 2022. https://doi.org/10.1080/01457632.2022.2079045. (**Taylor and Francis, SCI, IF = 2.172**)
3. **M. C. Gilago**, V.P. Chandramohan, " Performance parameters evaluation and comparison of passive and active indirect type solar dryers supported by phase change material during drying ivy gourd ," *Energy,* vol. 251, 2022. https://doi.org/10.1016/j.energy.2022.123998. (**Elsevier, SCI, IF = 8.857**)
4. **M. C. Gilago**, V. R. Mugi and V.P. Chandramohan., "Energy-exergy and environ-economic (4E) analysis while drying ivy gourd in a passive indirect type solar dryer without and with energy storage system and results comparison," *Solar Energy,* vol. 240, 2022. https://doi.org/10.1016/j.solener.2022.05.027. (**Elsevier, SCI, IF = 7.188**)
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1. **M. C. Gilago**, V. R. Mugi and V.P. Chandramohan, "Analysis and comparison of the performance parameters of passive and active indirect solar dryers with heat storage facility while drying carrot," Manuscript submitted on 18th December 2022, *Environmental Science and Pollution Research*. (**Springer, SCI, IF=5.19**)

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1. **M. C. Gilago** and V. P. Chandramohan, "The effect of using phase change material on the performance of natural convection indirect type solar dryer during drying ivy gourd," (ICRAM-2021), *Institute of Infrastructure, Technology, Research And Management*, 6-8 Aug, 2021, Ahmedabad, India.
2. **Mulatu C. Gilago**, Vishnu Vardhan Reddy Mugi, V.P. Chandramohan "Estimation of drying kinetics, performance parameters and results comparison of natural and forced convection indirect type solar dryers during drying ivy gourd" *Proceedings of the 26th National and 4th International ISHMT-ASTFE Heat and Mass Transfer Conference (IHMTC-2021)*, 17-20th December 2021, IIT Madras, Chennai-600036, Tamil Nadu, India, P.929-934. DOI: 10.1615/IHMTC-2021.1400
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4. **M. C. Gilago**, V. R. Mugi and V.P. Chandramohan, "Investigating the drying kinetics of pineapple in a passive indirect type solar dryer: comparative analysis without and with thermal energy storage system," *International symposium on energy management and sustainability ISEMAS-22*, 5th - 9th, April 2022, Piri Reis University, Istanbul, Turkey.