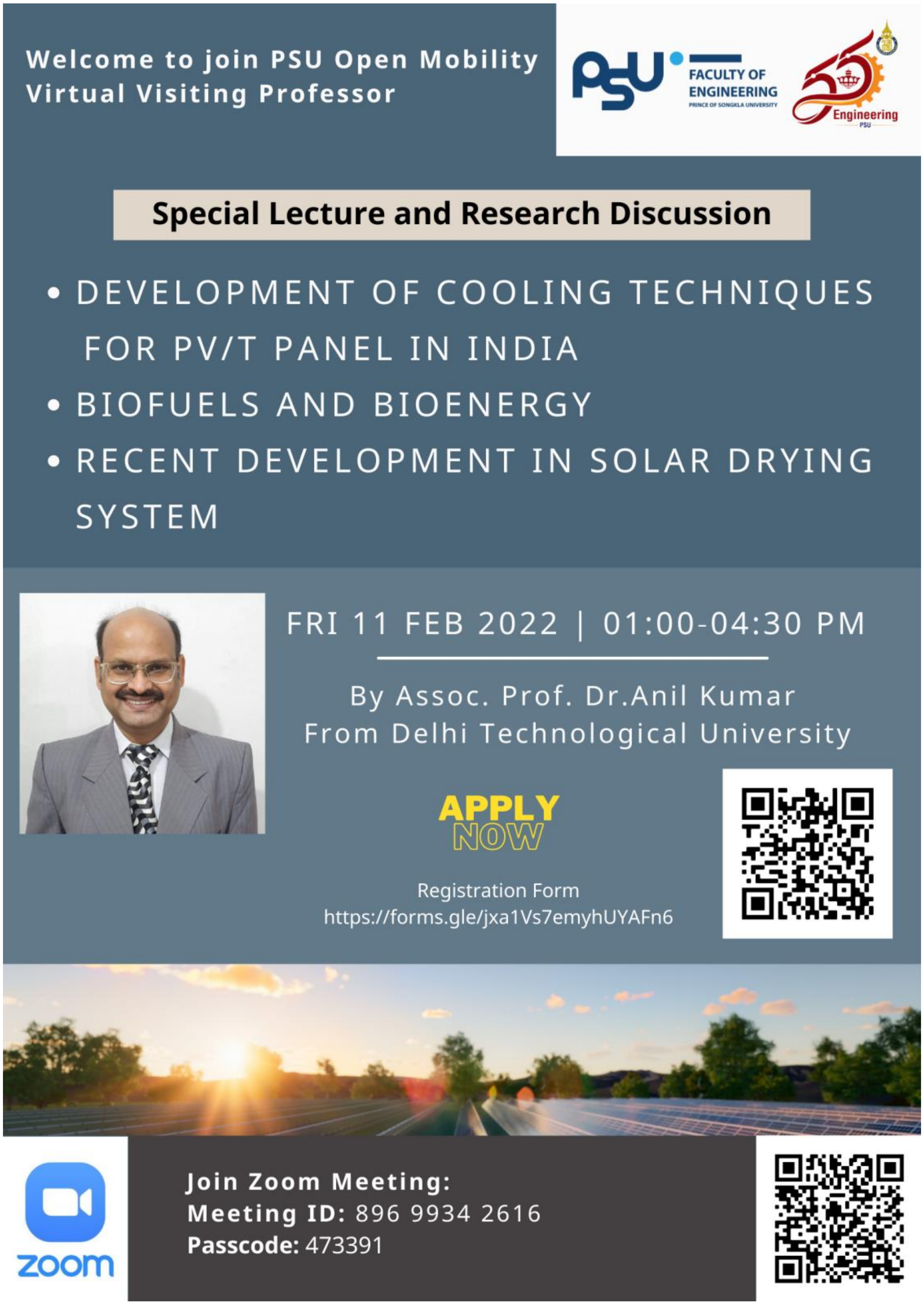
หลักฐานการบรรยายพิเศษภายใต้โครงการ Virtual Visiting Professor

หัวข้อบรรยายเรื่อง

1. Development of cooling techniques for PV/T panel in India.
2. Biofuels and bioenergy
3. Recent development in solar drying system

ประกอบด้วย

1. โปสเตอร์ประชาสัมพันธ์โครงการ
2. รูปกิจกรรมการบรรยาย
3. เอกสารประกอบการบรรยาย



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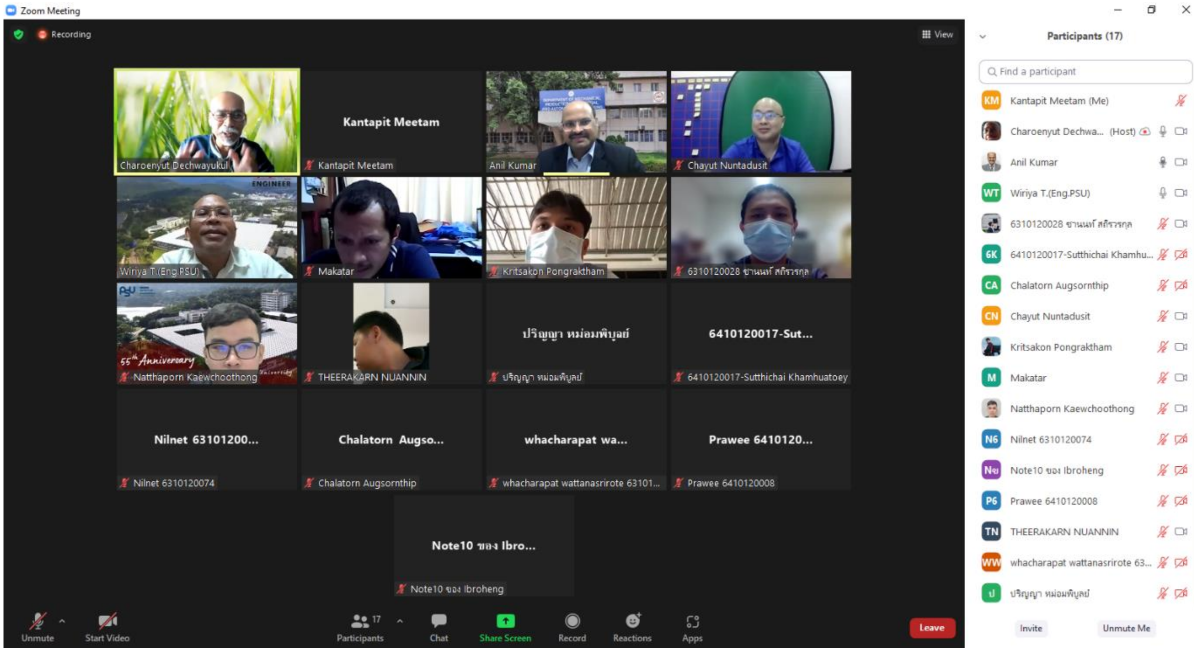
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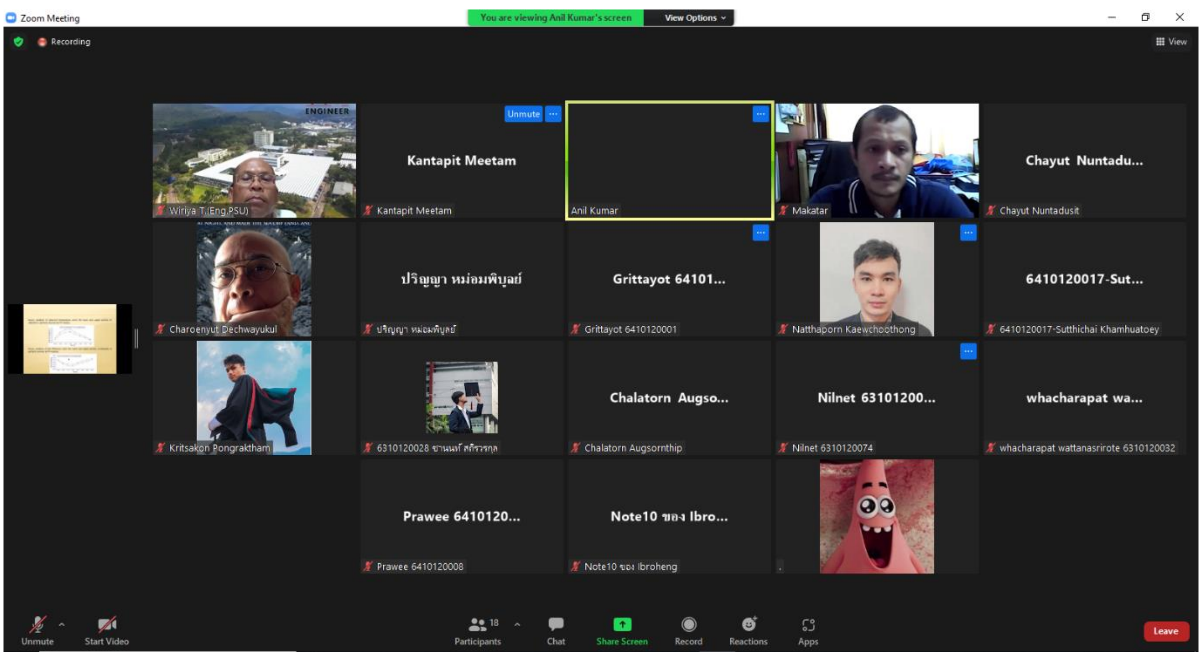
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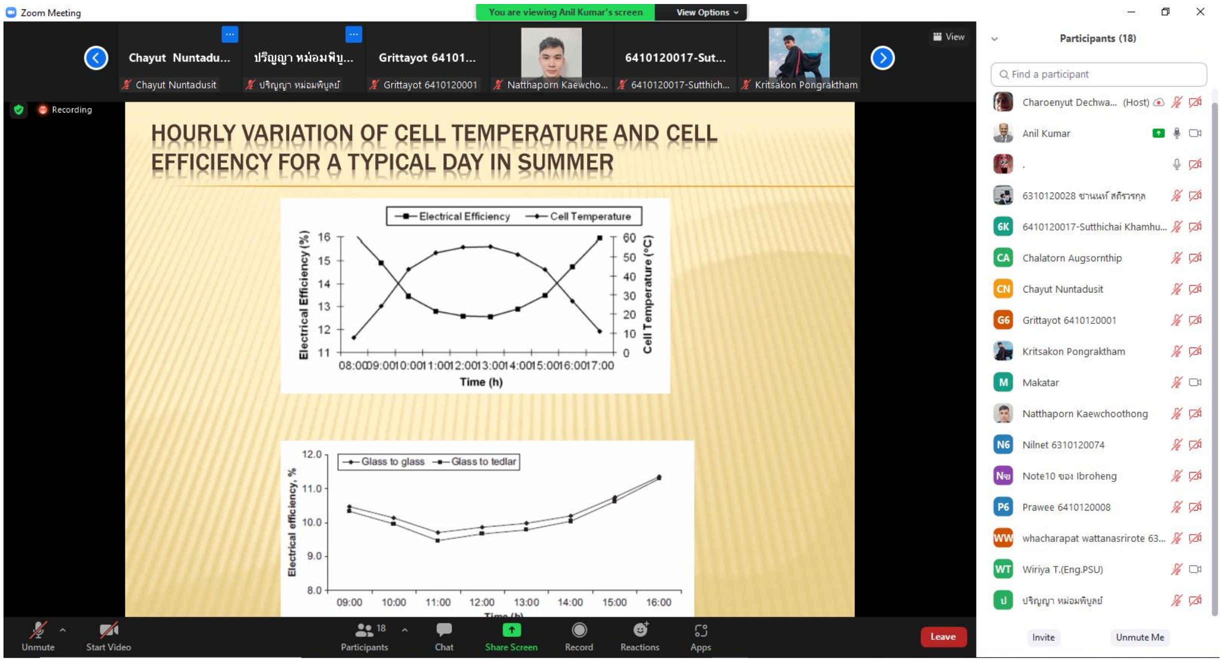

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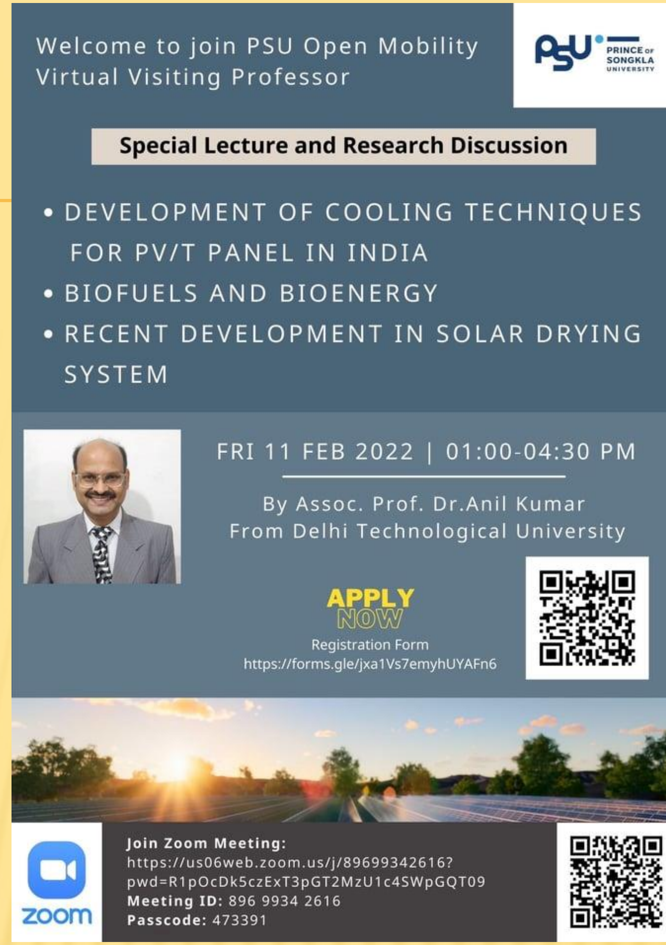

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Content

- Developments of Cooling Techniques for PVT Panel in India
- Bio Fuels and Bio Energy
- Recent Developments in Solar Drying systems in India

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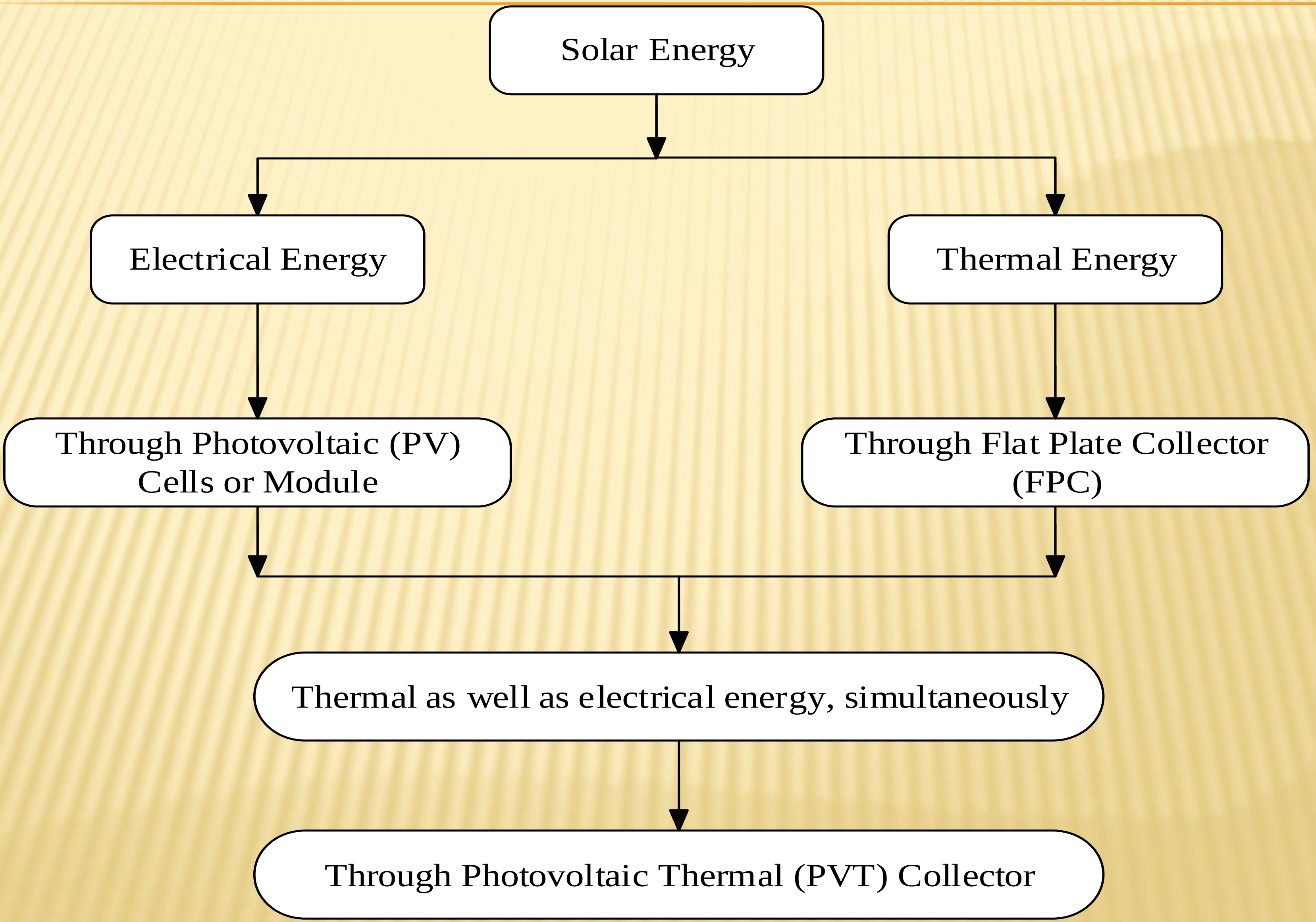
1. Developments of Cooling Techniques for PVT Panel in India

Introduction

What is PVT system

- Photovoltaic Thermal system is known as PVT system.
- PVT system is a hybrid system which is a combination of photovoltaic module and solar thermal collectors working in tandem.
- It simultaneously produces electrical energy and thermal energy by utilising solar radiation.
- PVT system enabling PV cooling and simultaneously utilizing the extracted heat for domestic, agriculture, industrial purposes etc.
- The efficiency of PVT system is higher than the PV module and solar thermal collectors when deployed alone.

Flow diagram of utilization of solar energy.



A typical representation of PVT collector

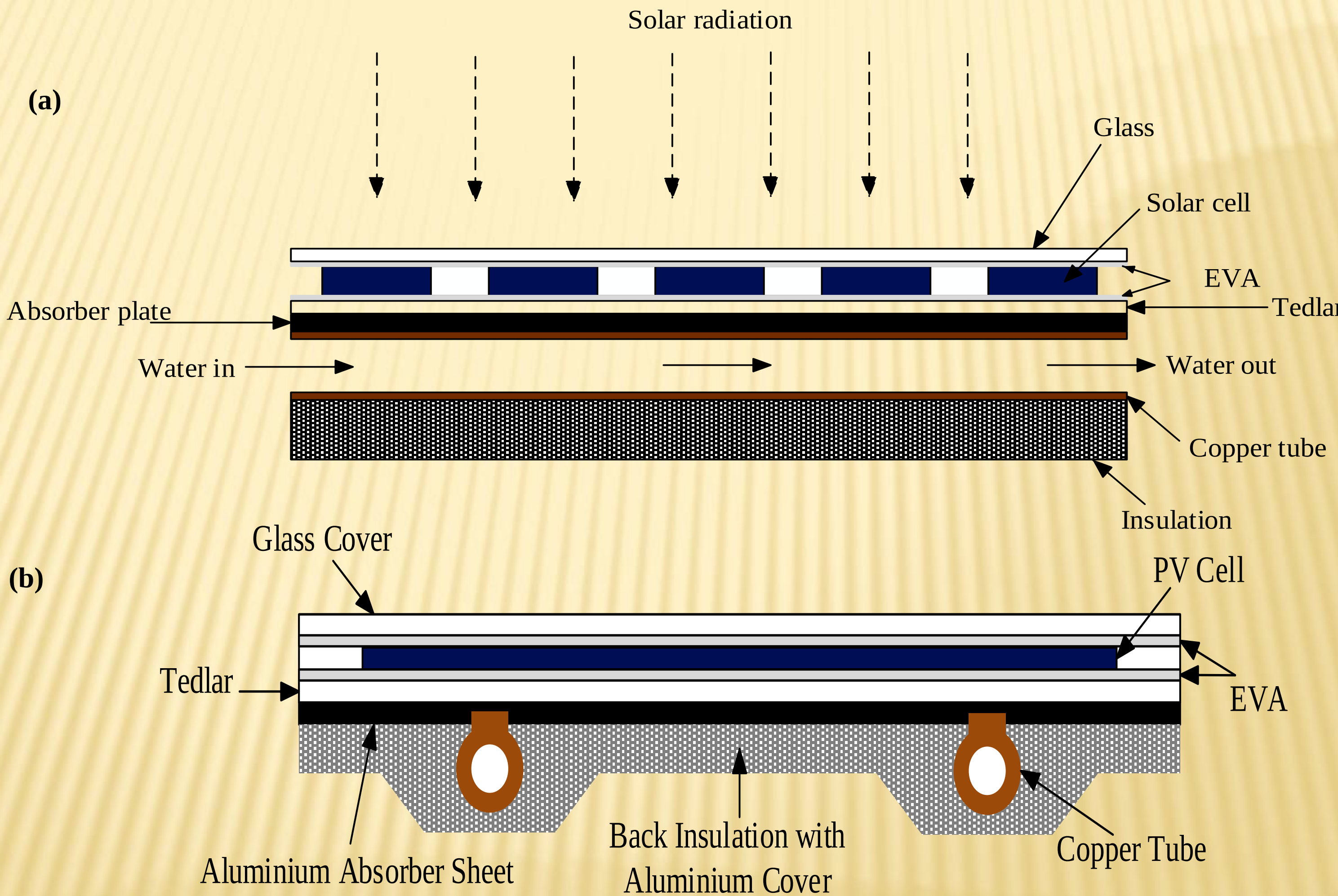


Fig. (a). Horizontal cut sectional view of photovoltaic thermal (PVT) collector. **(b).** Vertical cut sectional view photovoltaic thermal (PVT) collector.

Basic Idea of PVT collector Efficiency

Solar Thermal Collector

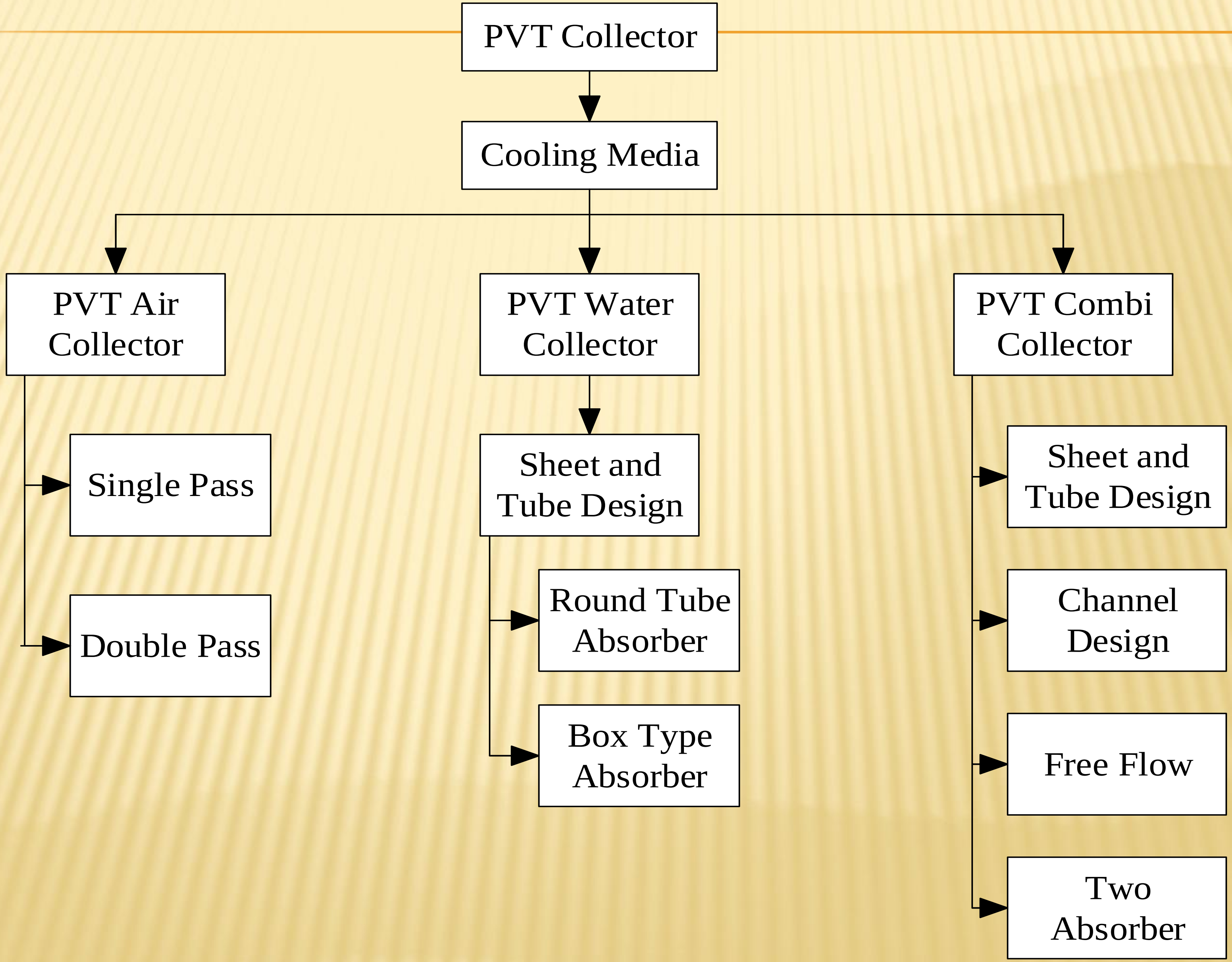
PV Module

PVT collector

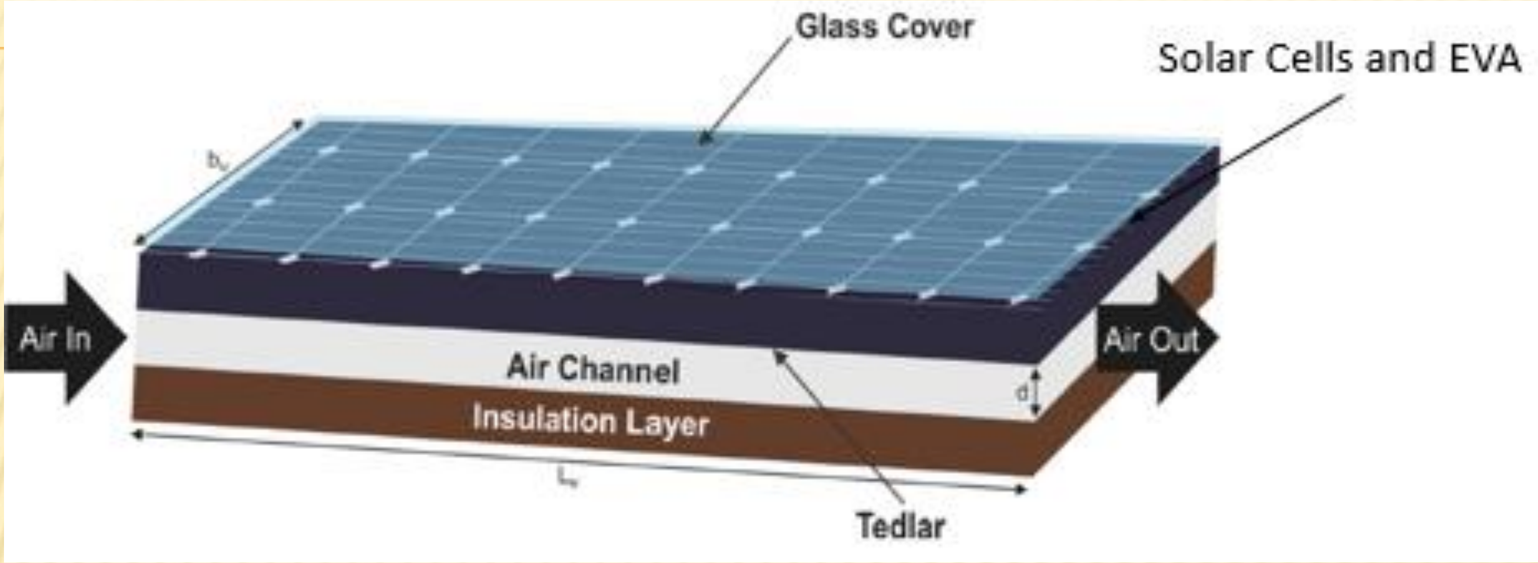
- Total Area of Collector = Area of Thermal Collector + Area of PV Module
- Total Efficiency = (Thermal Efficiency + PV Efficiency)/2
- Thermal Efficiency = 60%
- PV Efficiency = 10%
- Combined Photovoltaic Thermal Efficiency = 35%

- Total Area of Collector = Area of Thermal Collector + Area of PV Module
- Total Efficiency = Thermal Efficiency + PV Efficiency
- Thermal Efficiency = 35%
- PV Efficiency = 15%
- Combined Photovoltaic Thermal Efficiency = 50%

Cooling of PVT system



PVT Air Collector



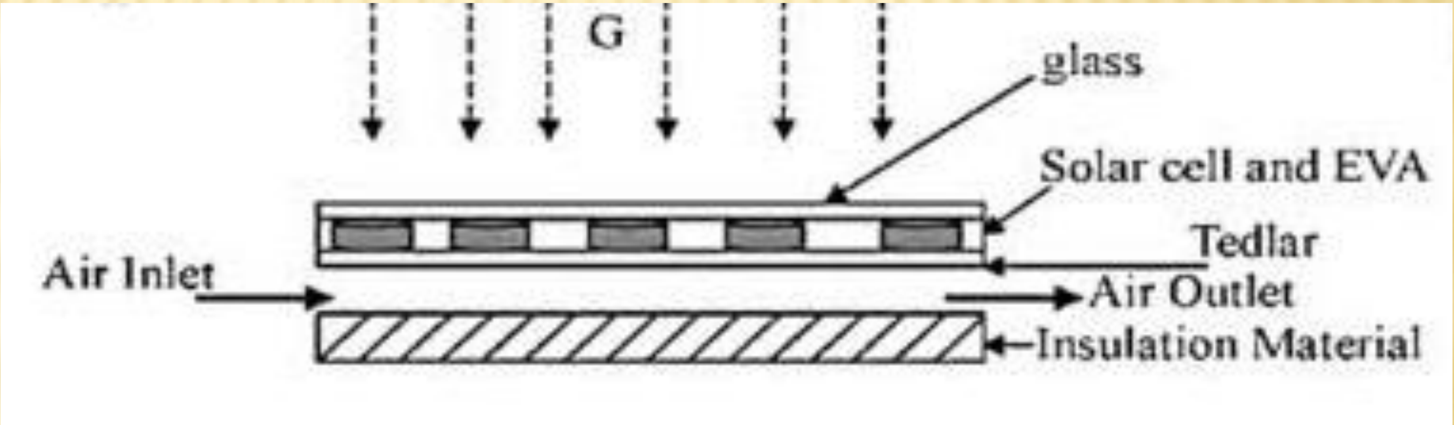


Fig. A typical representation of PVT air collector (a) Layered diagram of PVT air collector (b) Cross sectional view PVT air collector

Single Pass PVT Air Collector

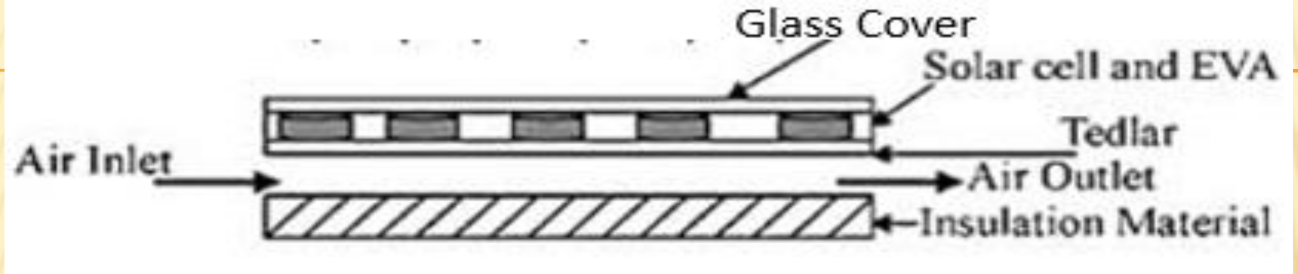


Fig. A typical representation of Single Pass PVT air collector

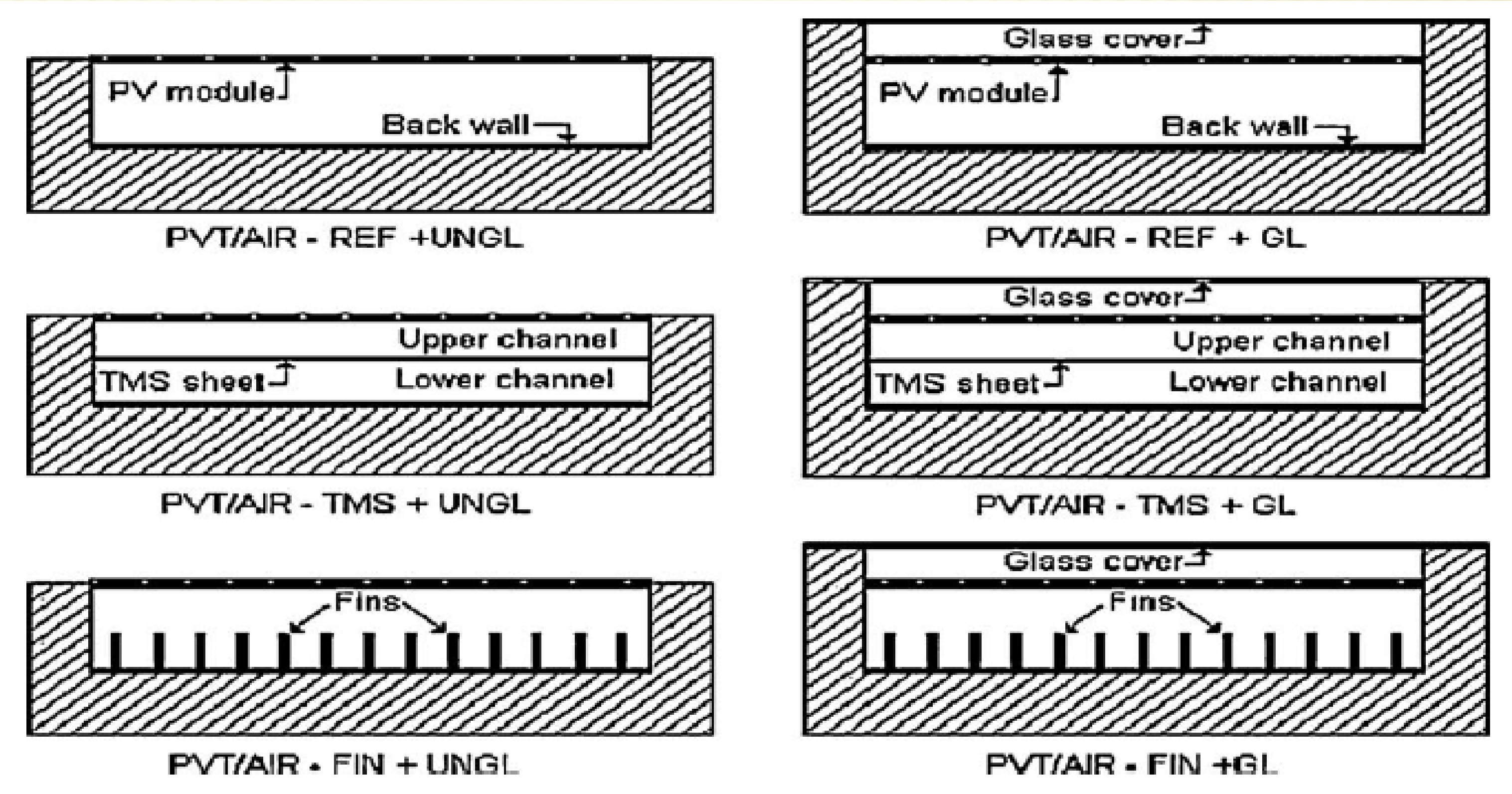


Fig. Cross-section Various model of Single Pass PVT air collector

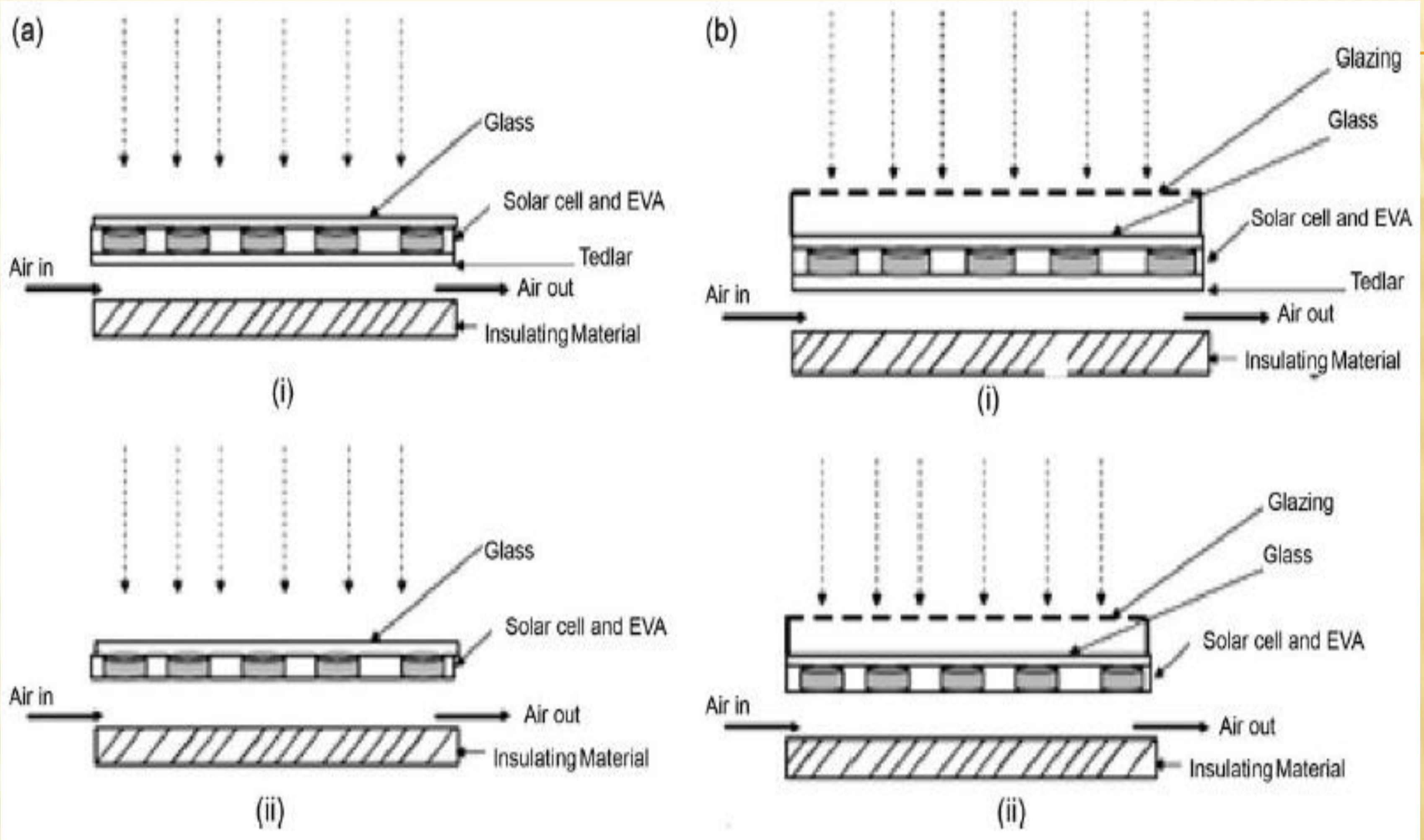
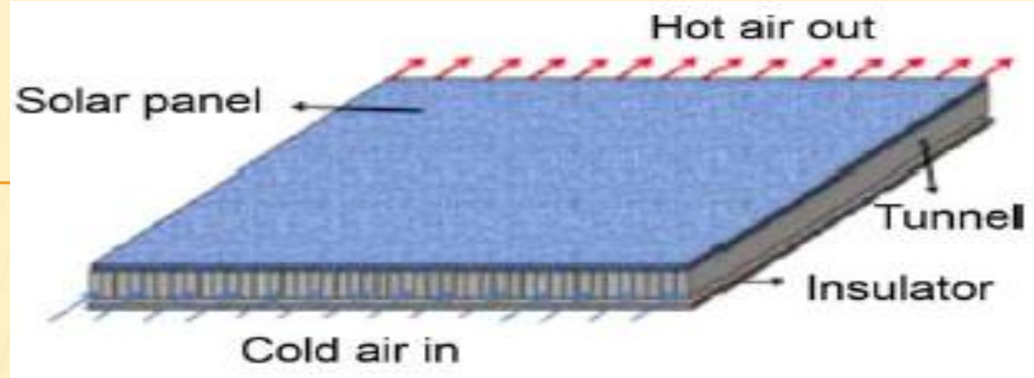


Fig. Cross-section of Single Pass PVT air collector (a) Unglazed PVT air collector: (i) with tedlar and (ii) without tedlar; (b) Glazed PVT air Collector: (i) with tedlar and (ii)without tedlar

(a)



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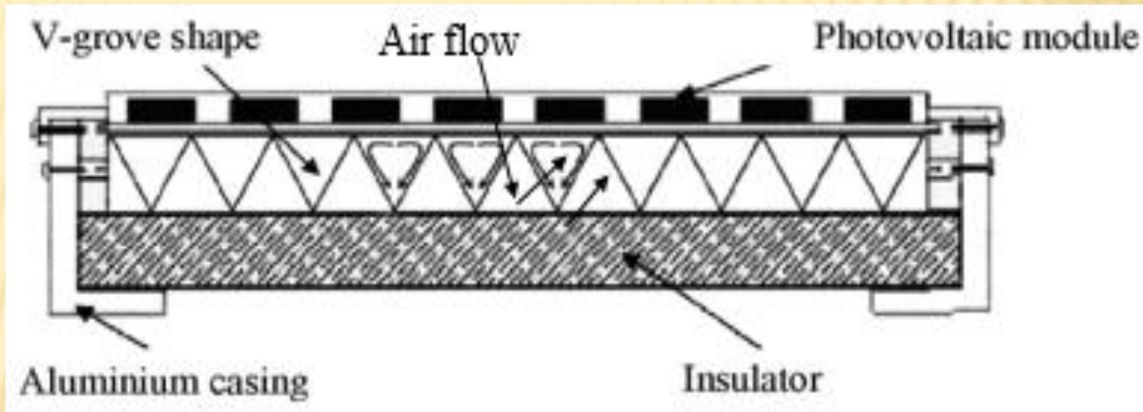

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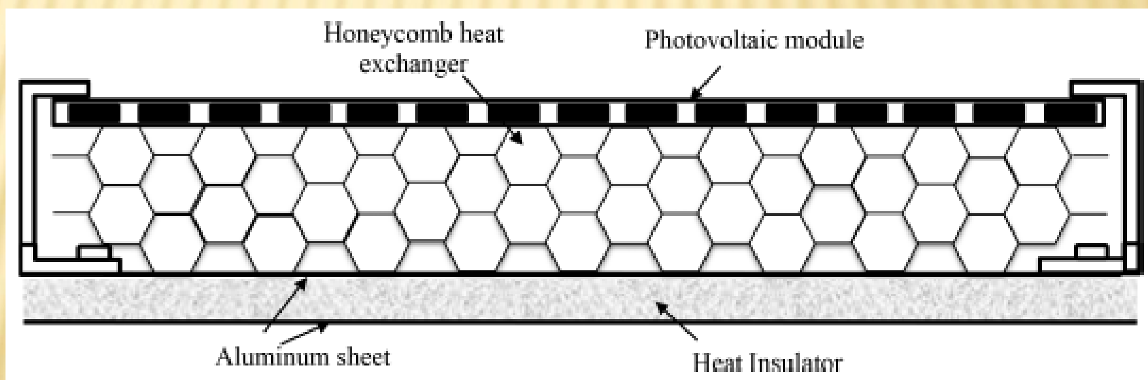
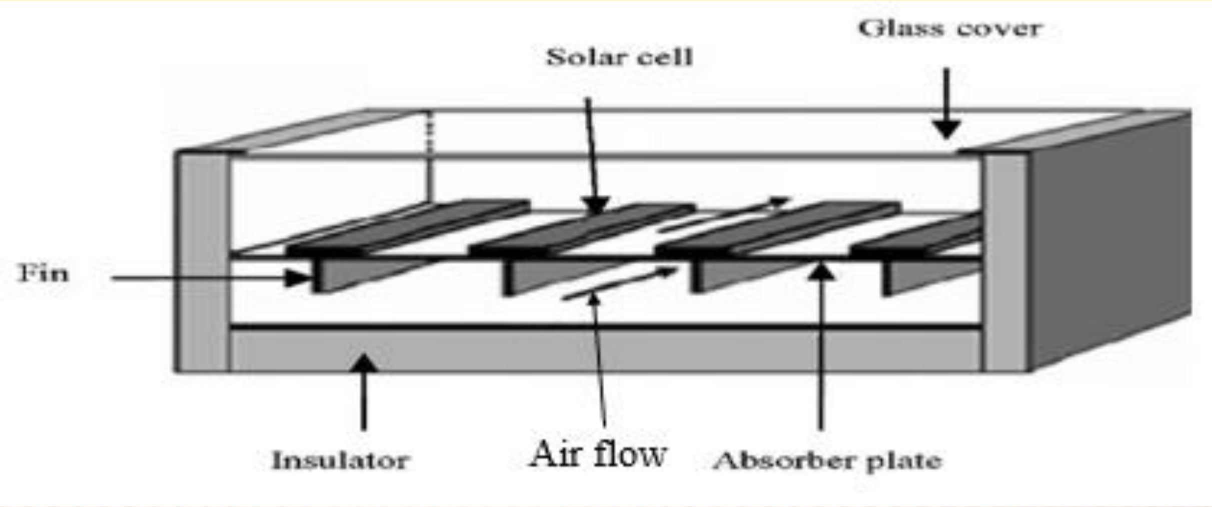


Fig. Single Pass PVT air collector with (a) rectangular tunnel design, (b) V-groove heat exchanger and (c) Honeycomb heat exchanger

(a)



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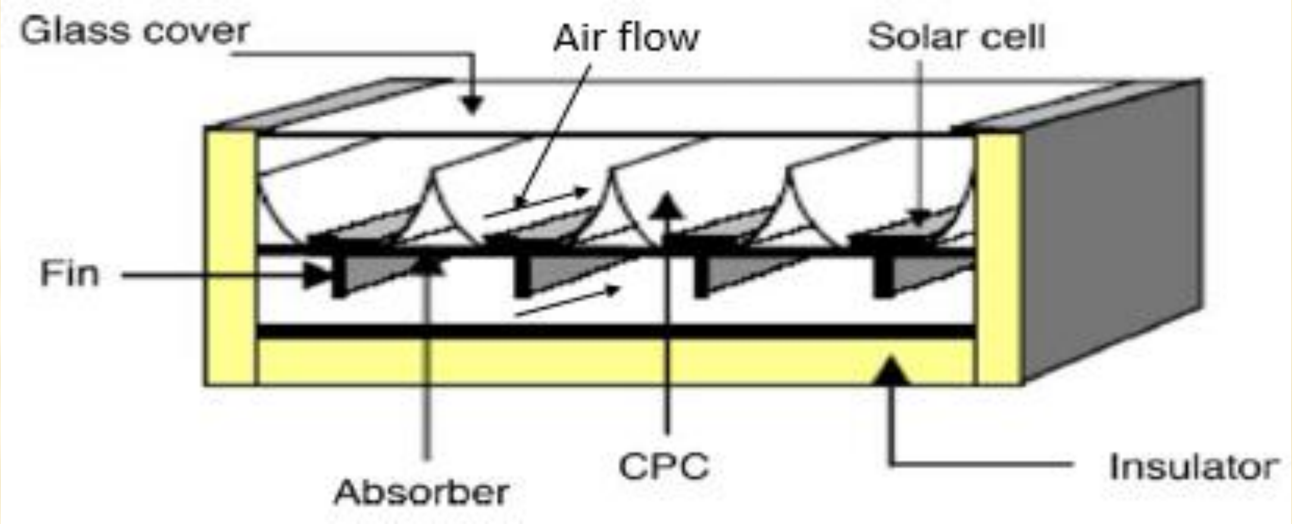


Fig. Single Pass PVT air collector with (a) finned double duct air collector and (b) compound parabolic concentrator (CPC) and finned double duct air collector

Double Pass PVT Air Collector

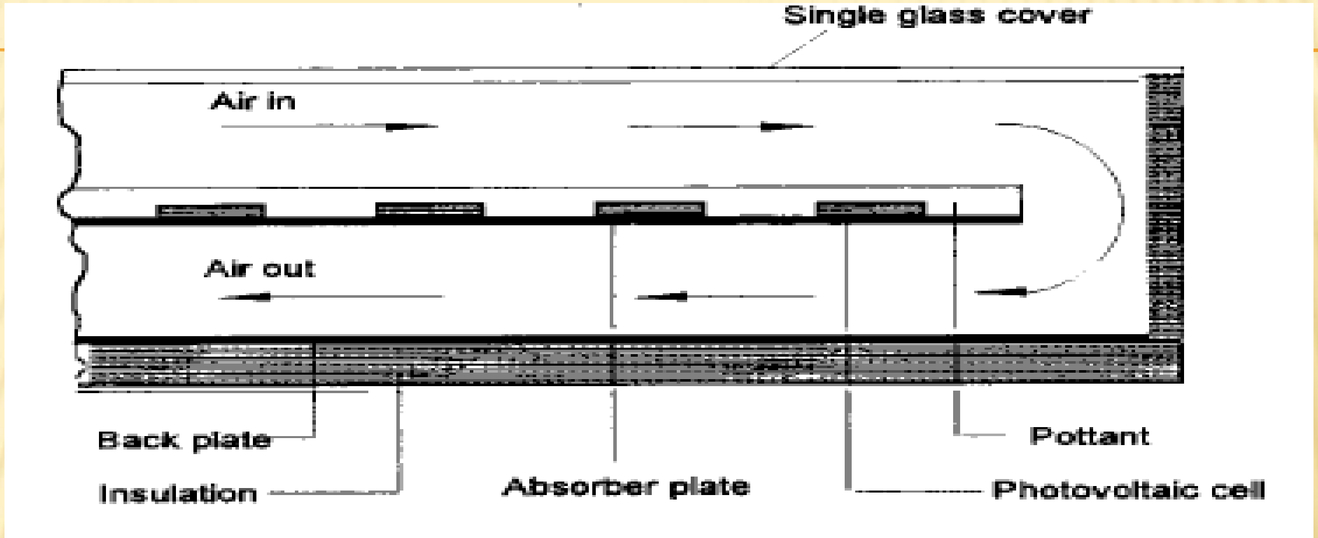


Fig. A typical representation of Double Pass PVT air collector

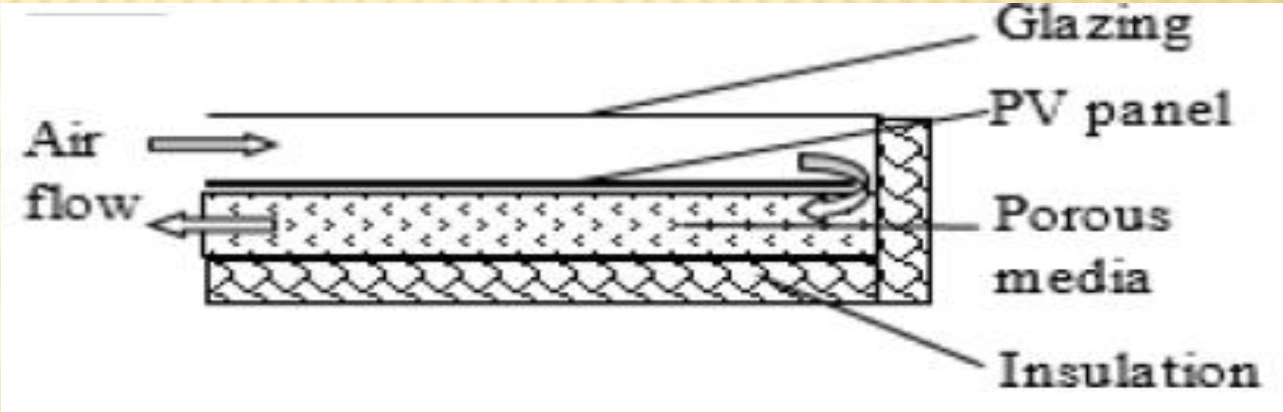
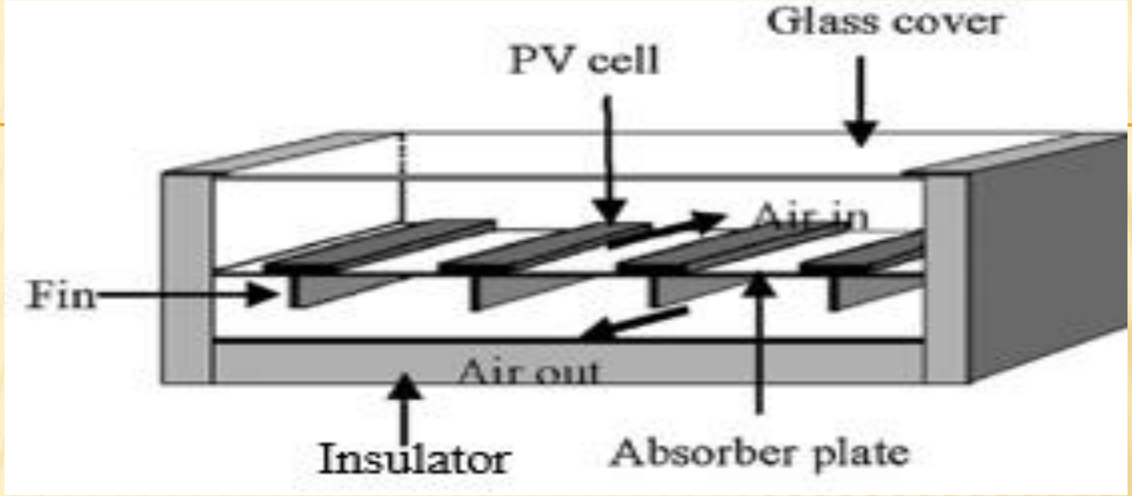


Fig. Cross-section of Double Pass PVT air collector with porous media in lower channel

(a)



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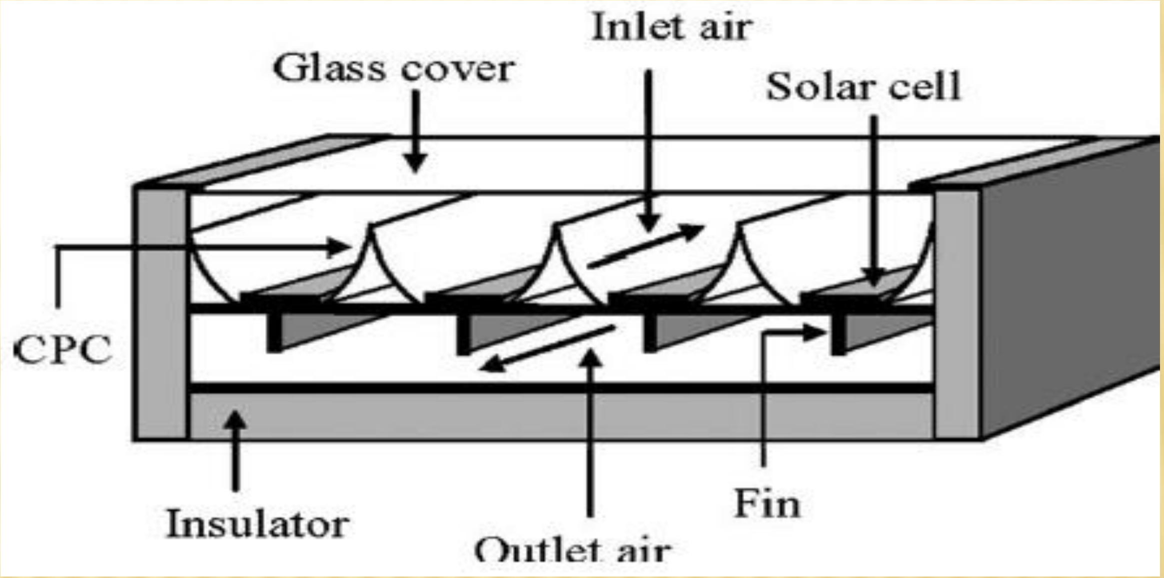


Fig. Double Pass PVT air collector with (a) finned and (b) compound parabolic concentrator (CPC) and finned air collector

Recent advancement in PVT Air Collector

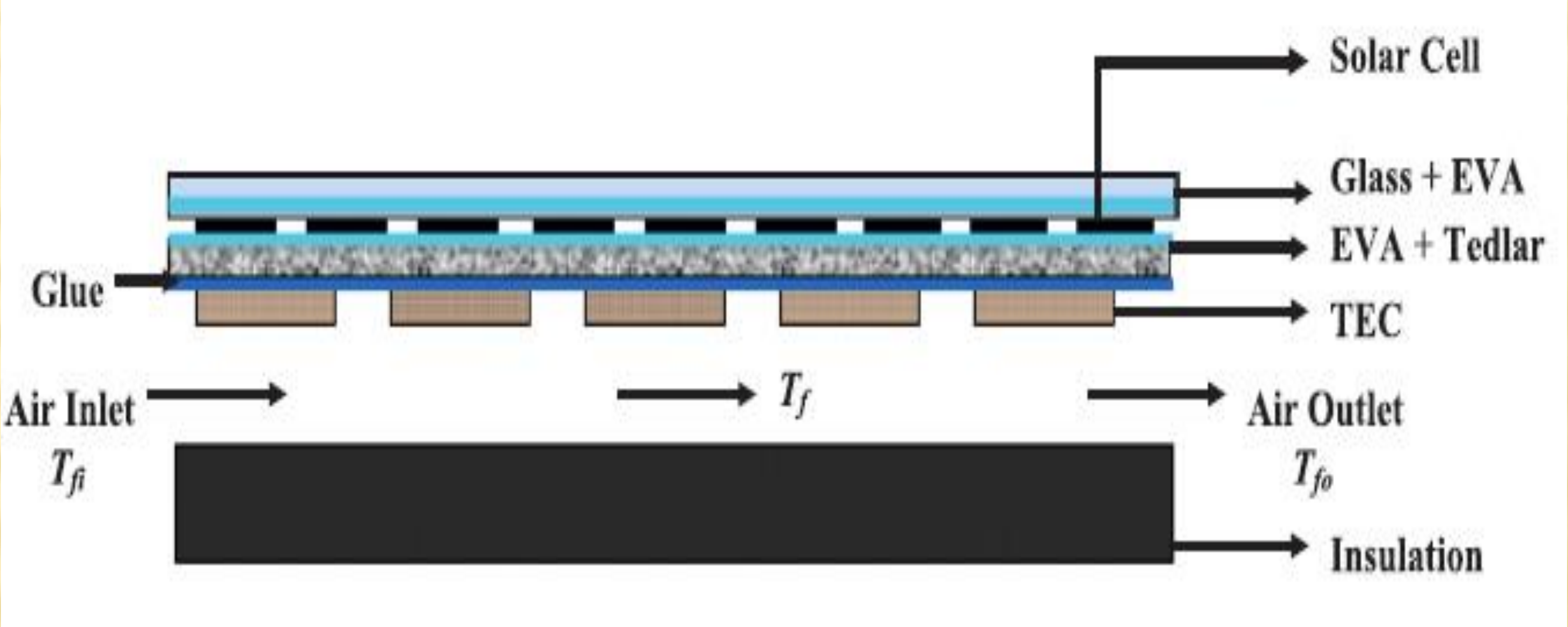
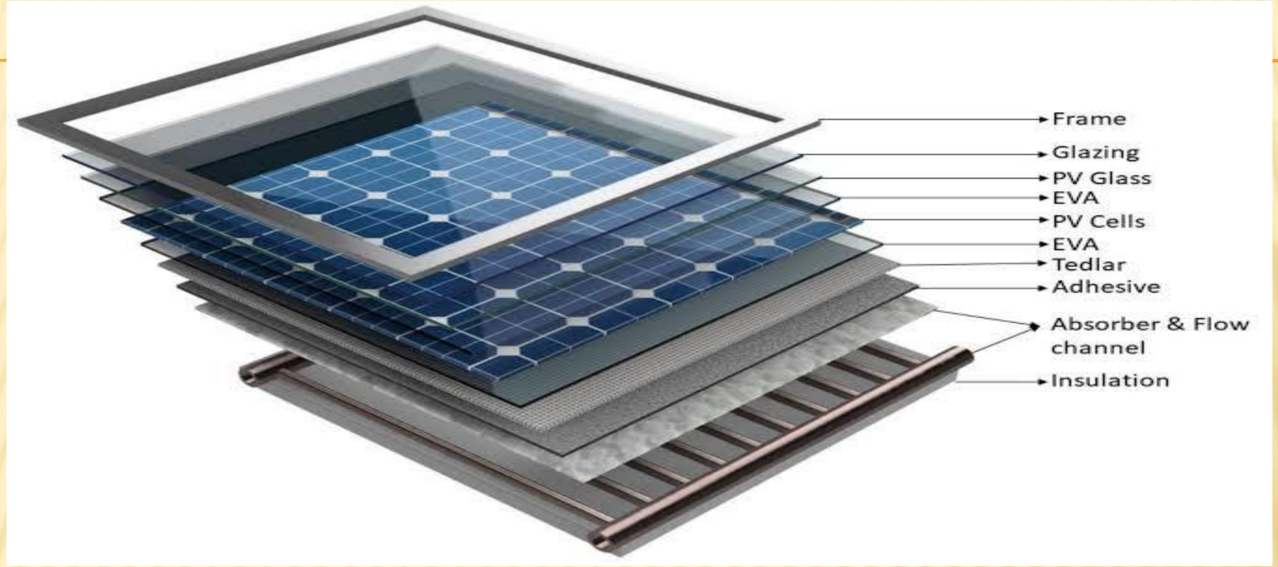


Fig. A typical representation of PVT air collector with Thermoelectric Cooler (TEC)

PVT Water Collector

(a)



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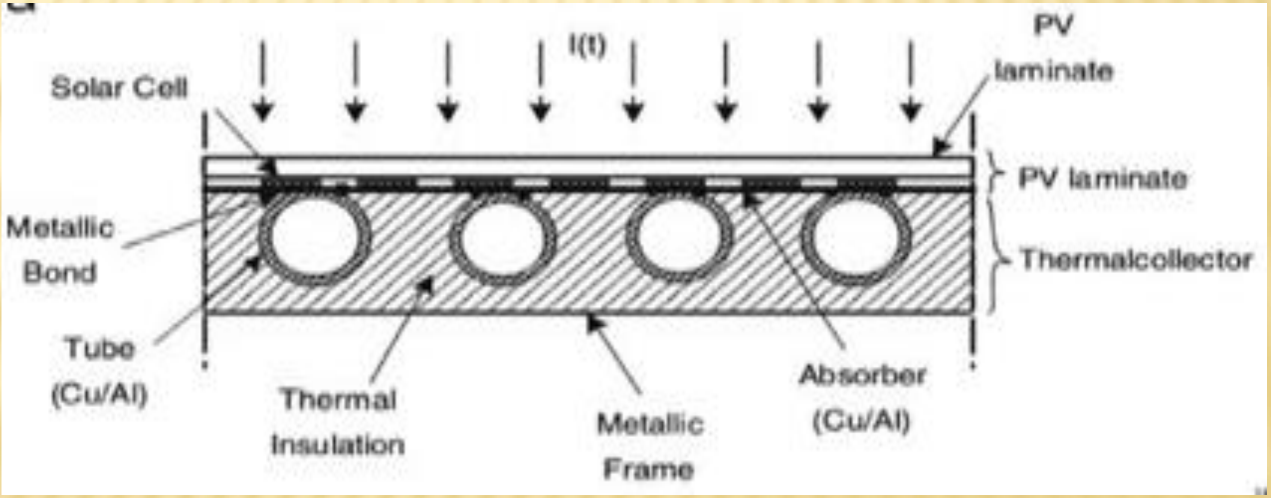
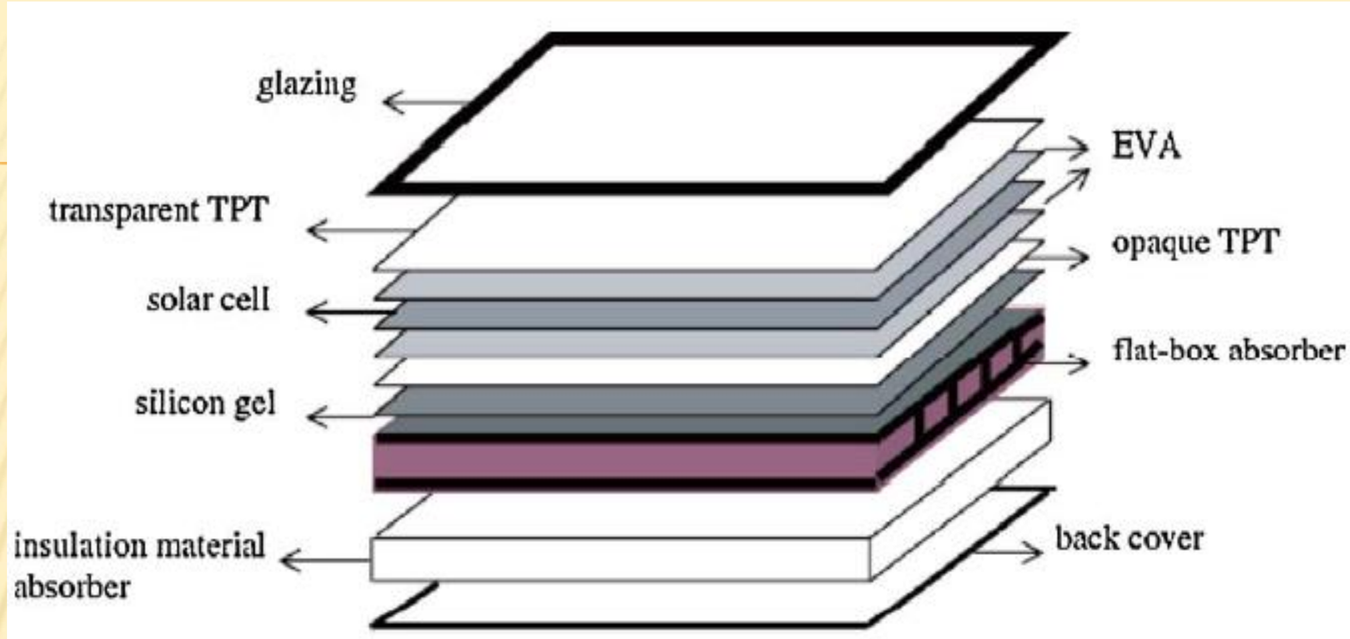


Fig. A typical representation of round tube absorber PVT water collector (a) Layered diagram (b) Cross sectional view

(a)



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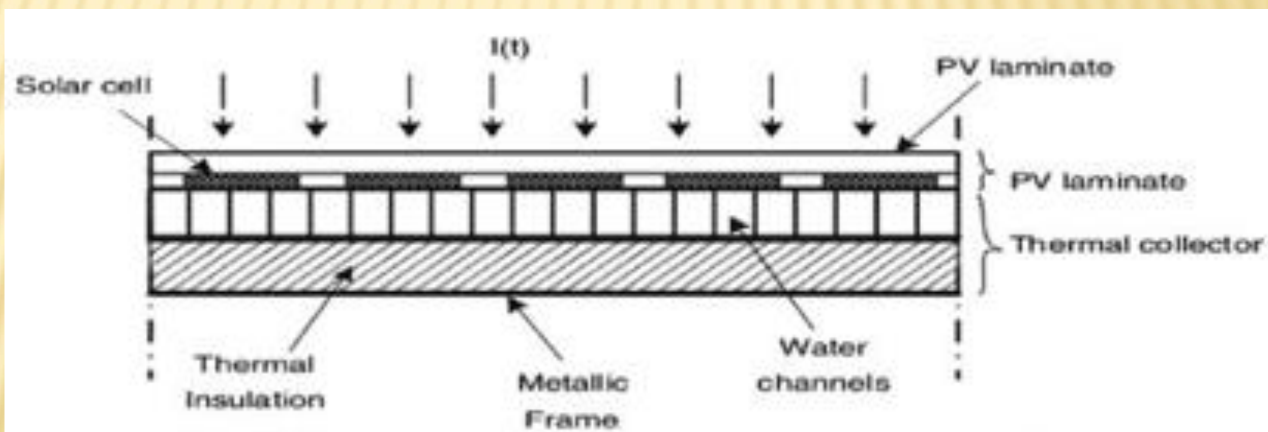


Fig. A typical representation of Box type absorber PVT water collector (a) Layered diagram (b) Cross sectional view

Various flow configuration of absorber of PVT Water Collector

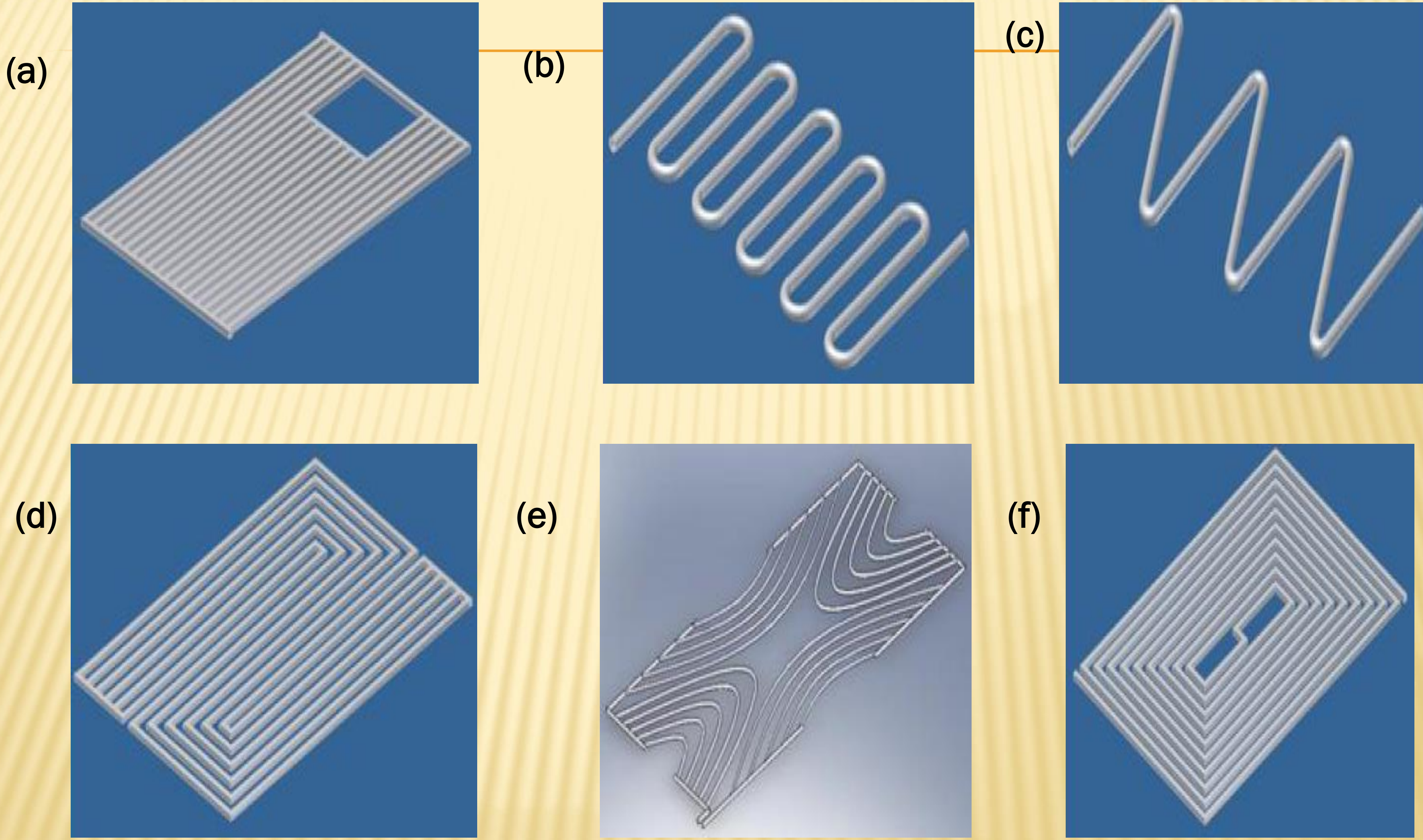


Fig. (a)Direct flow, (b) Oscillatory flow, (c) Serpentine flow, (d) Parallel Serpentine flow, (e) Web Flow and (f) Spiral flow

PVT Combi (Combination of Water & Air) Collector

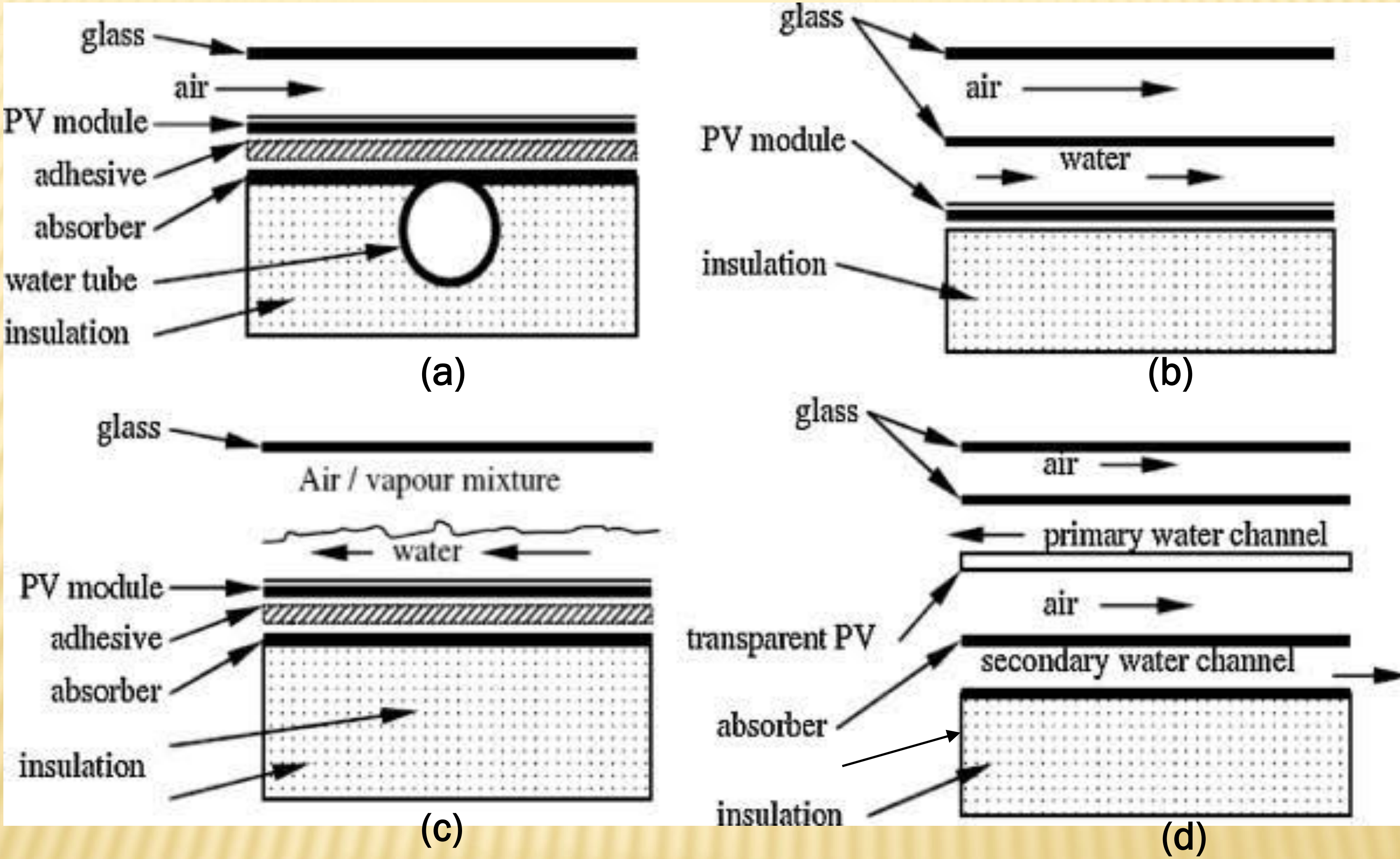


Fig. PVT Combi collectors (a) Sheet and Tube Design , (b) Channel Design, (c) Free flow and (d) Two Absorber Design

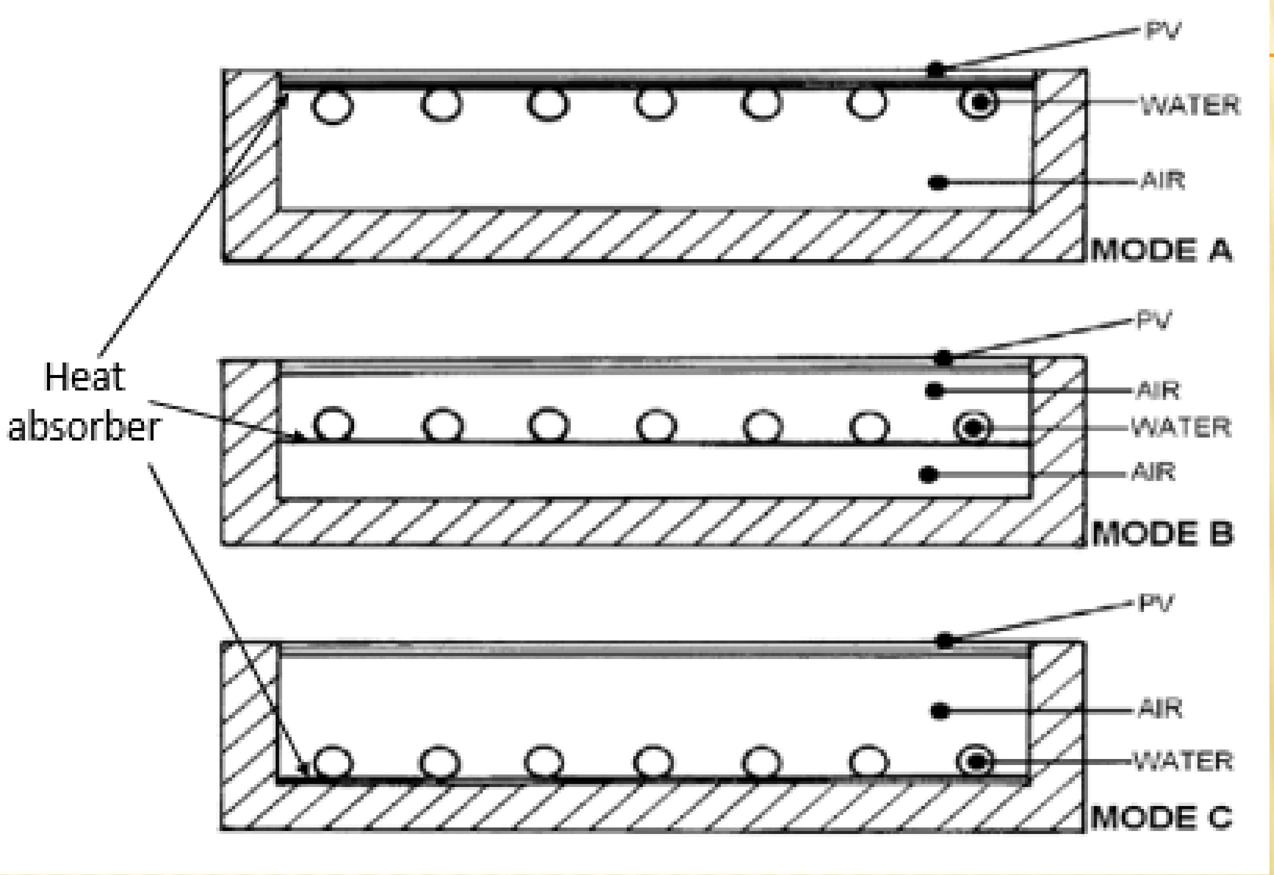


Fig. Alternative PVT combi collectors design modes used to determine the optimum arrangement of the water and air heat exchanger

Recent advancement in PVT Water Collector

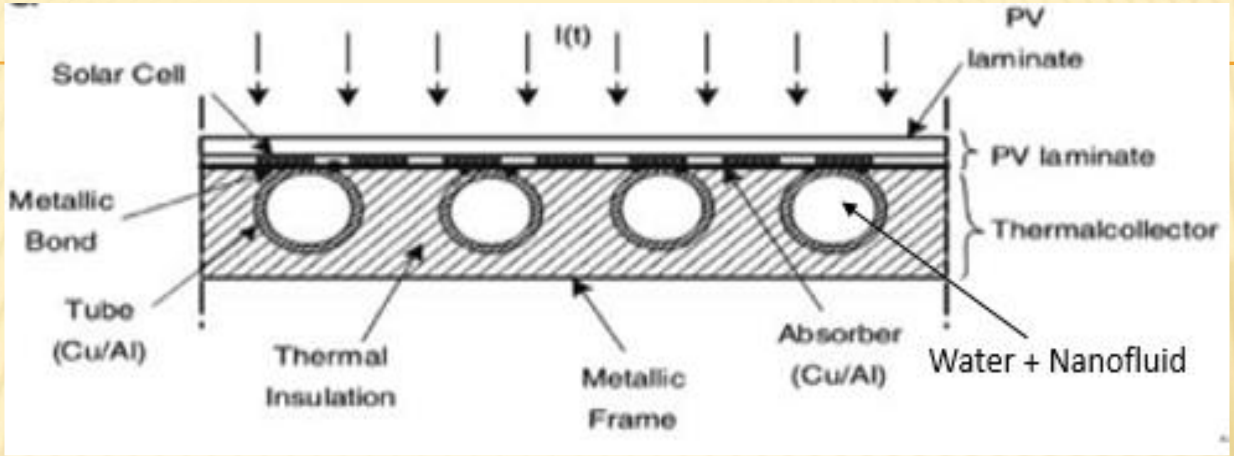


Fig. PVT Water collector with Nanofluid

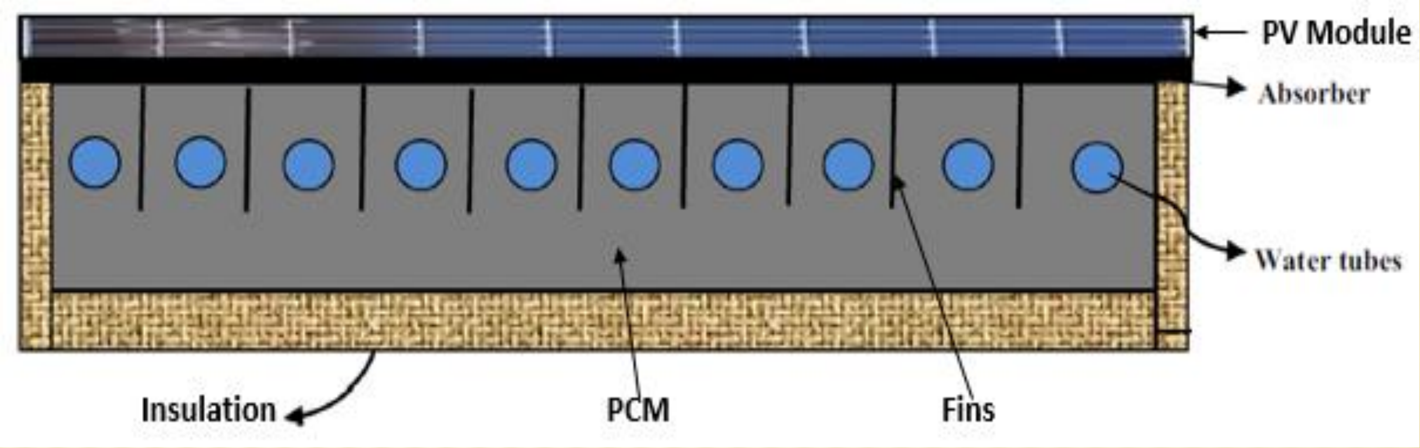


Fig. PVT Water collector with PCM

Thermal Modelling of PVT Collector

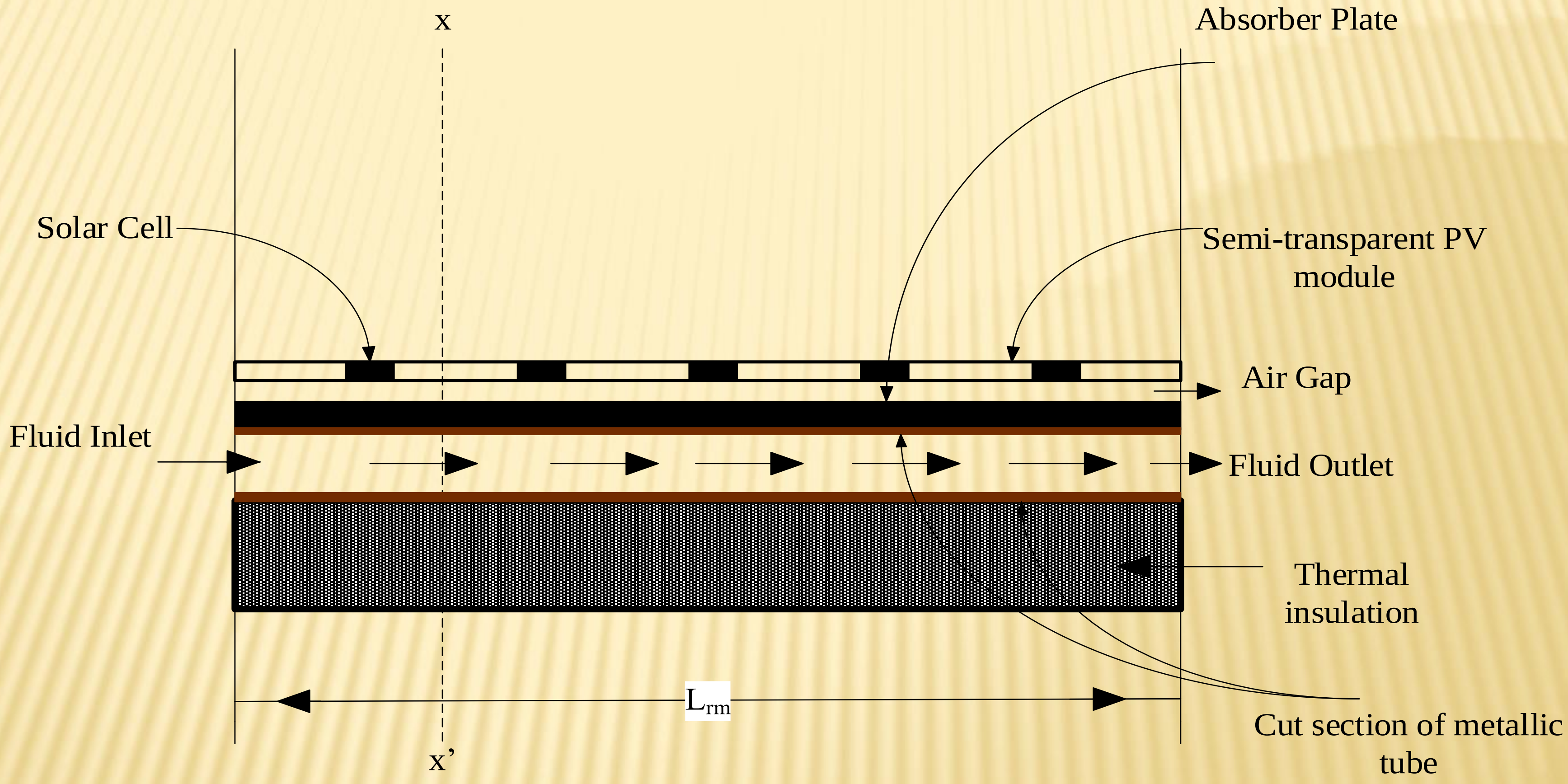


Fig. A typical representation of cross-sectional side view of Photovoltaic Thermal (PVT) Collector

Assumptions

In order to simplify the mathematical model, following assumptions are considered to write energy balance equations for :

(a) The configuration of PVT collector has been considered in quasi-steady state condition,

(b) One-dimensional heat conduction is a good approximation for the present modelling,

(c) The heat capacity of solar cell, absorber plate, glass cover, reflector and insulation materials has been neglected and

(d) The ohmic losses between two solar cells have been neglected.

Energy Balance for PVT collector

- ***Energy balance equation for solar cell PVT collector:***

[The rate of solar radiation received by solar cells] = [The rate of heat loss from solar cells to ambient through top glass surface] + [The rate of heat transferred from solar cells to absorber pate through the glass] + [The rate of electrical energy generated by PV module]

$$\alpha_c \tau_g \beta_c I_u A_m = U_{t,ca}(T_c - T_a)A_{rm} + U_{t,cp}(T_c - T_p)A_{rm} + \eta_c \tau_g \beta_c I_u A_m$$

- ***Energy balance for absorber plate of PVT collector:***

[The rate of solar energy available on absorber plate through non-packing area of PV module] + [The rate of heat transferred from solar cell to absorber plate] = [The rate of heat transferred to fluid flowing in tubes below the absorber plate] + [The rate of heat transferred from absorber pate to ambient]

$$\alpha_c {\tau_g}^2 (1 - \beta_c) I_u A_m + U_{t,cp}(T_c - T_p)A_m = F' h_{pf}(T_p - T_f)A_m + U_{t,pa}(T_p - T_a)A_m$$

- ***Energy balance for flowing water in tube as fluid below the absorber plate:***

[The rate of thermal energy carried away by flowing water] = [The rate of thermal energy transferred from absorber plate to flowing water]

$$\dot{m}_f C_f \frac{dT_f}{dx} dx = F' h_{pf}\left(T_p - T_f\right) b dx$$

Using the above energy balance, above equation can be rewritten as given below:

$$\dot{m}_f C_f \frac{dT_f}{dx} dx = F'[PF_2(\alpha\tau)_{m,eff} I_u - U_{Lm}(T_f - T_a)] b dx$$

Above Eq. can be solved by using initial condition, $T_f|_{x=0} = T_{fi}$, the solution can be obtained as given below:

$$T_f = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_u}{U_{Lm}} + T_a\right]\left[1 - exp\left\{\frac{-F' U_{Lm} bx}{\dot{m}_f C_f}\right\}\right] + T_{fi} exp\left\{\frac{-F' U_{Lm} bx}{\dot{m}_f C_f}\right\}$$

Further, the temperature of fluid at the outlet of the PVT collector can be obtained as follows:

$T_{fo} = T_f|_{x=L_{rm}}$, or

$$T_{fo} = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_u}{U_{Lm}} + T_a\right]\left[1 - exp\left\{\frac{-F' U_{Lm} b L_{rm}}{\dot{m}_f C_f}\right\}\right] + T_{fi}\, exp\left\{\frac{-F' U_{Lm} b L_{rm}}{\dot{m}_f C_f}\right\}$$

or,

$$T_{fo} = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_u}{U_{Lm}} + T_a\right]\left[1 - exp\left\{\frac{-F'{}_{U_{Lm}} A_m}{\dot{m}_f C_f}\right\}\right] + T_{fi}\, exp\left\{\frac{-F'{}_{U_{Lm}} A_m}{\dot{m}_f C_f}\right\}$$

Later on, the rate of useful heat gain at the outlet of PVT can be estimated as follows:

$$\dot{Q}_u = \dot{m}_f C_f \left(T_{fo} - T_{fi}\right)$$

On substitution of above Eqs., the expression for $\dot{Q}_u$ can be represented as follows:

$$\dot{Q}_u = A_m F_{Rm}\left[PF_2(\alpha\tau)_{m,eff} I_b - U_{Lm}\left(T_{fi} - T_a\right)\right]$$

The temperature dependent electrical efficiency of solar cell of PV module of the collector is given as follows:

$$\eta_c = \eta_0[1 - \beta_0(\mathrm{T}_c - T_0)]$$

Now, using above Eq., the electrical efficiency and electrical power output of module of PVT can be evaluated as follows:

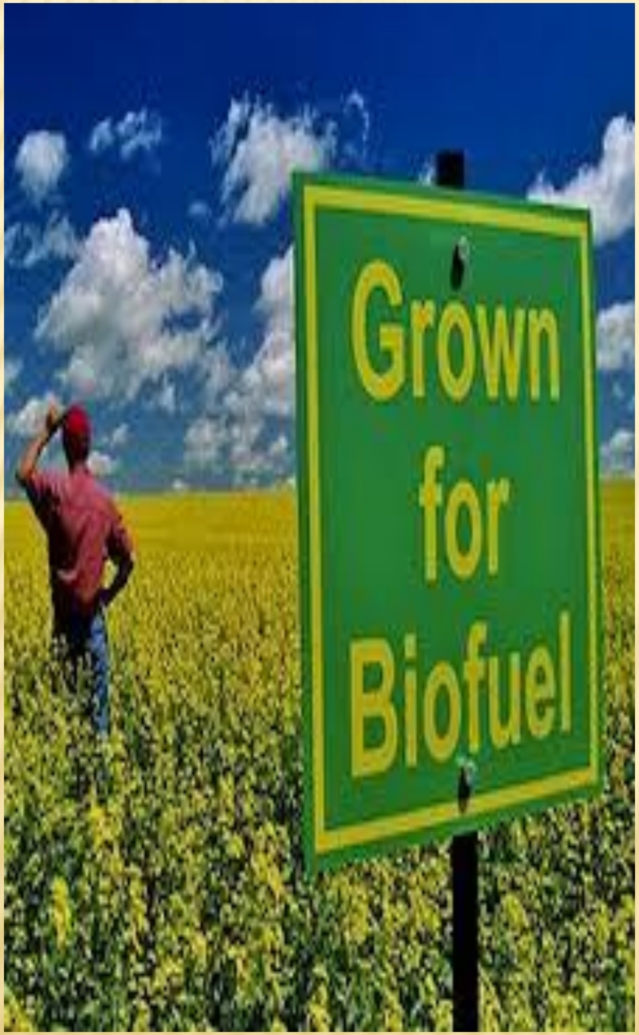
$$\eta_m = \tau_g \beta_c \eta_c$$

and,

$E_{el} = \eta_m A_m I_u$ respectively.

2. Bio Fuels and Bio Energy

INTRODUCTION



- Today, the use of biofuels has expanded throughout the globe.
- Some of the major producers and users of biogases are Asia, Europe and America.
- There are several factors that decide the balance between biofuel and fossil fuel use around the world. Those factors are cost, availability, and food supply
- . There is only so much land fit for farming in the world and growing biofuels necessarily detracts from the process of growing food. As the population grows, our demands for both energy and food grow. At this point, we do not have enough land to grow both enough biofuel and enough food to meet both needs.

CONTINUED..

- Some of the agricultural products that are specially grown for the production of biofuels are:
- United States- switchgrass, soybeans and corn
- Brazil-sugar cane
- Europe- sugar beet and wheat
- China- cassava and sorghum
- Asia- miscanthus and palm oil
- India- jatropha

CURRENT TRENDS

- Most gasoline and diesel fuels in North America and Europe are blended with biofuel.
- Biodiesl accounts for about 3% of the German market and 0.15% of the U.S. market.
- About 1 billion gallons of biodiesel are produced annually.
- Bioethanol is more popular in the Americas while biodiesel is more popular in Europe.
- The U.S. and Brazil produce 87% of the world's fuel ethanol.
- More than 22 billion gallons of fuel ethanol are produced each year.
- Ethanol is added to gasoline to improve octane and reduce emissions.
- Biodiesel is added to petroleum-based diesel to reduce emissions and improve engine life.
- Concerns about the global price of food have resulted in many nations revising (downward) plans for biofuel production and use.

APPLICATIONS OF BIOFUELS

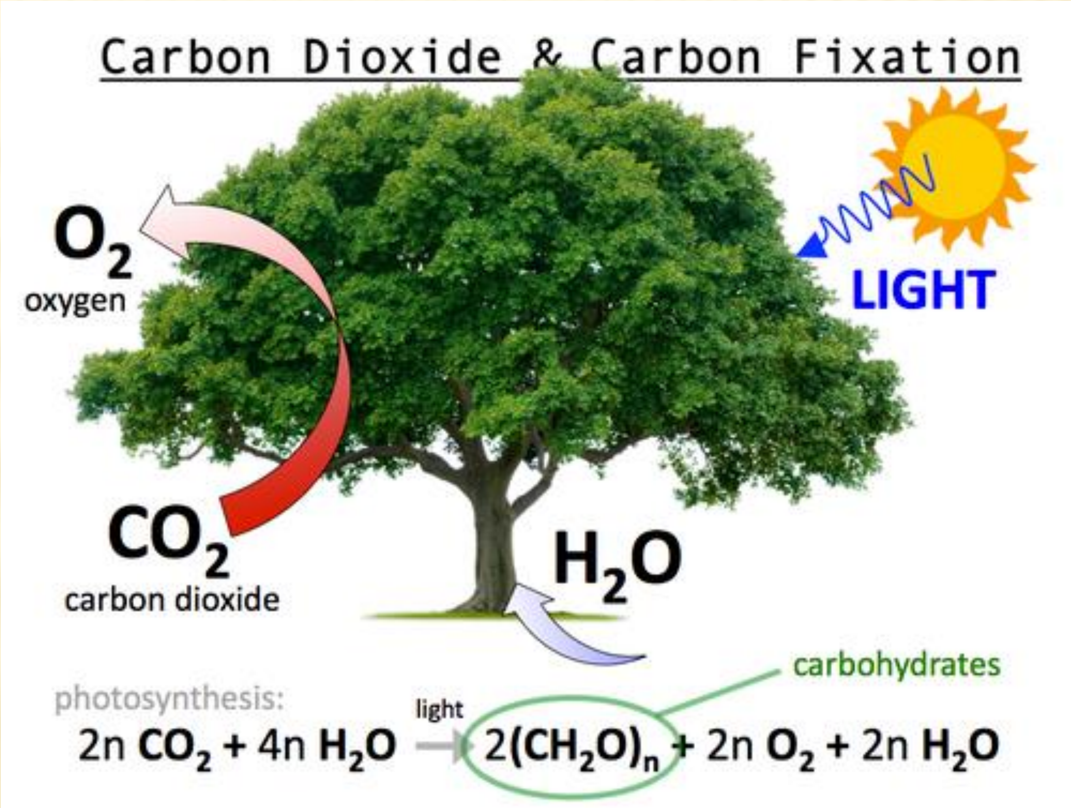
- Transportation
  - Leading application because vehicles require clean, dense, high power fuels in a liquid state
  - Liquids can be easily pumped and stored
- Power Generation
  - solid biomass fuel like wood
- Heat

WHAT IS A BIOFUEL?

- Biofuel (AKA agrofuel): any fuel whose energy is obtained through a process of biological carbon fixation
- Carbon Fixation
  - A chemistry process that converts carbon dioxide into a hydrocarbon molecule (a source of energy) that would be found in a living organism
  - If this process occurs in a living organism, it is referred to as "biological carbon fixation"

A LESSON LEARNED FROM NATURE

Photosynthesis is a biological carbon fixation process utilized by plants to obtain energy in the form of carbohydrates



WHAT IS BIOMASS?

Biomass is dead organic matter

- Examples: kernels of corn, mats of algae, stalks of sugar cane

Types of biomass

- Woody
  - Examples: coconut, oil palm, poplar, pine
  - Generally burned to heat space or heat water to produce steam to generate electricity via a turbine generator
    - When utilized directly: direct biomass
- Non-Woody
  - Examples: corn, sugar cane, soybeans, algae
  - Generally processed to produce different liquid biofuels
    - Indirect biomass

PRODUCING BIOFUEL FROM BIOMASS

- Biomass energy can be converted into liquid biofuels generally in two methods:
- Method I
  - Sugar crops or starch are grown and through the process of fermentation, ethanol is produced.
- Method II
  - Plants are grown which naturally produce oil, such as jatropha and algae
  - These oils are heated to reduce their viscosity after which they are directly used as fuel for diesel engines
  - This oil can be further treated to produce biodiesel which can be used for various purposes

BIOFUELS ARE COUNTERPARTS

Biofuels are counterparts to traditional fossil fuels

Biofuel	Fossil Fuel
Ethanol	Gasoline/Ethane
Biodiesel	Diesel
Methanol	Methane
Biobutanol	Gasoline/Butane

COMPARING ENERGY CONTENT

- The energy content of biodiesel is about 90% that of its counterpart petroleum diesel
- The energy content of butanol is about 80% that of gasoline
- The energy content of ethanol is about 50% that of gasoline

BIOFUEL CARBON FOOTPRINT

Most biofuels are at least as energy dense as coal, but produce less carbon dioxide when burned.

WHY RENEWABLE?

- Biofuels are produced from biomass or bio waste, which can be replenished year after year through sustainable farming practices
  - Biomass and biofuel are renewable
- Fossil fuels require millions of years to form
  - Fossil fuels are NOT renewable

GREEN ENERGY…?

- "Renewable" is NOT the same as "Green"
- A renewable energy source simply does not deplete
  - Example: solar, wind, hydroelectric
- A "green" energy is ALSO good for the planet because it does not harm ecosystems, contribute to acid rain, or worsen global warming
- Solar energy is green and renewable
- All 'green' energy is considered renewable, but not all renewable energy is green
- Biofuels are examples of renewable energy sources that are not always green because they produce greenhouse gases.

WOODY BIOMASS

- **Coconut** - In areas with abundant coconut trees, after harvesting the meat or edible part of the coconut, the hull is converted into a bio briquette. The benefit of this biomass is that it burns efficiently and leaves very little residue. This has resulted in bio briquettes being used for cooking, particularly in underdeveloped countries.
- **Oil Palm** - The oil palm provides biomass in two ways. The fruit produces oil, which can be harvested and chemically converted to produce biodiesel. After the oil is harvested, however, the hulls can be burned directly. Thus, oil palm provide both direct and indirect biomass.
- **Poplar** - The poplar family includes trees like the Aspen and Cottonwood. These trees are valued for their rapid growth, reasonable resistance to disease, ability to provide habitat, and ability to be cultivated from sprouts cut from adult trees (reduces overall cost in the long term).
- **Pine** - Pine is valued for many of the same reasons as poplar. It grows fast, it's easy to cultivate, and is relatively inexpensive to grow.

HISTORY OF BIOFUELS

- Biofuels are nothing new. In fact, they've been around as long as cars have. **Henry Ford** originally designed the Model T to run on *ethanol*. And people have been running diesel engines on *vegetable oil* much longer than they have been running diesel engines on petroleum-based diesel fuel.
- **Rudolf Diesel**, inventor of the diesel engine, originally designed it to run on *vegetable oil*. In fact, one of his early demonstrations, at the World Exhibition in Paris in 1897, had a diesel engine running on *peanut oil*.
- Petroleum based fuel originally won out over biofuel because of cost. The table is slowly turning though as fossil fuels become more expensive.
- During World War II, the demand for biofuel increased once again as fossil fuels became less abundant.
- Biofuel surged in popularity during the energy crisis of the 1970s.
- The most recent surge in biofuel popularity occurred in the 1990s in response to tougher emissions standards and increasing demands for enhanced fuel economy.

CONTINUED….

- **Ancient times-late 1800s** – People use biomass materials (which today include plants and plant-derived materials, manure and even garbage) in the form of burning wood for cooking, warmth and steam production. By the late 1800s, wood was being replaced by coal as the primary means of steam generation.
- **1826** – Ethanol was first prepared synthetically through the independent efforts of Henry Hennel in Britain and S.G. Sérullas in France.
- Samuel Morey developed an engine that ran on ethanol and turpentine.

CONTINUED….

- **1850s** – Ethanol is used as a lighting fuel.
- **1860s** – During the US Civil War, a liquor tax was placed on ethanol whisky to raise money for the war. The tax increased the price of ethanol so much that it could no longer compete with other fuels such as kerosene in lighting devices. Ethanol production declined sharply because of this tax and production levels did not begin to recover until the tax was repealed in 1906

CONTINUED….

- **1919** – When Prohibition began in the US, ethanol was banned because it was considered a liquor. It could only be sold when it was mixed with petroleum.
- **1920s** – Standard Oil began adding ethanol to gasoline to increase octane and reduce engine knocking. With 9 million automobiles in the United States, gas stations are opening everywhere.
- **1933** – Prohibition ended in the US and ethanol was used as a fuel again.
- **1940s** – Ethanol use increases temporarily during World War II when oil and other resources are scarce.
- First US fuel ethanol plant is built in Omaha, Nebraska.

CONTINUED….

- **1970s** – Interest in ethanol as a transportation fuel was revived when embargoes by major oil producing countries cut gasoline supplies. Since that time ethanol use has been encouraged by offering tax benefits for producing ethanol and for blending ethanol into gasoline.
- **1975** – Brazil formed the Pro-Álcool Program (Programa Nacional do Álcool, or National Alcohol Program) to reduce foreign oil dependence. This program used government financing to move toward ethanol use in lieu of fossil fuels. Brazil began making ethanol from sugar cane.

CONTINUED….

- **1980s** – After investing heavily in renewable fuels in the 1970s, Brazil kept the program alive during the 1980s. With its robust ethanol program, Brazil developed an extensive ethanol industry.
- By the mid-1980s, ethanol-only cars accounted for almost 90 percent of all new-auto sales in Brazil, making the country the biggest alternative fuel market in the world.

CONTINUED….

- **1984** – Burlington Electric in Vermont builds a 50-megawatt wood-fired plant to produce electricity.
- **1988** – Ethanol began to be added to gasoline for the purpose of reducing carbon monoxide emissions.
- **1989** – Canada and the United States conduct pilot trials of direct wood-fired gas turbine plants.
- **1990** – Biomass's electricity generation reaches 6 gigawatts.

CONTINUED….

- **2000** – Brazil deregulated the ethanol market and removed its subsidies. However, depending on market conditions, all fuels are required to be blended with 20-25% ethanol.
- **2003** – Since 2003, ethanol has grown rapidly as the oxygenating factor for gasoline in the US. Flex-fuel vehicles were introduced. These vehicles can run on straight ethanol, straight gasoline or a blend of the two. Today, the majority of new cars sold in Brazil are flex-fuel.

CLASSIFICATION OF BIOFUELS

Biofuels are classified into three generations.

1ST GENERATION BIOFUELS

- 1st generation biofuels are also called conventional biofuels. They are made from things like *sugar*, *starch*, *or vegetable oil*. Note that these are all food products. Any biofuel made from a feedstock that can also be consumed as a human food is considered a first generation biofuel.
- It is important to note that the structure of the biofuel itself does not change between generations, but rather the source from which the fuel is derived changes.
- 1st generation biofuels suffer from the same problems including *threatening the food chain*, *increasing carbon emissions* when planted outside traditional agricultural settings, and intense growth requirements. Ultimately, first generation biofuels have given way to second and third generation fuels.
- Though they will continue to provide biofuel for the foreseeable future, their importance is waning and new, better alternatives are being developed.

CORN

- US is the world leading producer of corn and ethanol made from corn.
- As of 2012, more than 40% of US corn crop was being used to produce corn-based ethanol

Benefits:

- Existing infrastructure for planting, harvesting, and processing corn.
- Corn starch to ethanol conversion is relatively simple.
- No indirect land use costs.

Disadvantages

- Low ethanol yield per acre of corn produced
- Requires large amounts of pesticides and fertilizers
- Soil and water contamination, expensive
- Takes a significant amount of corn away from the global food supply raising global food prices and leading to hunger in underdeveloped countries

SUGAR CANE

- The majority of the world's sugar cane is grown in **Brazil**, which was the world's largest producer of alcohol fuel until very recently went it was eclipsed by the United States. Brazil produces roughly **5 billion gallons or 18 billion liters** of fuel ethanol annually. The country adopted a very favorable stance on ethanol derived from sugar cane as a result of the oil embargo of the 1970s. Brazil has a policy of at least **22% ethanol** in its gasoline, though 100% ethanol is available for purchase.
- Unlike corn, sugar cane provides sugar rather than starch, which is more easily converted to alcohol. Where as corn requires heating and then fermentation, sugar cane requires only fermentation.
- Advantages of sugar cane include:
  - Infrastructure for planting, harvesting, and processing that is already in place.
  - No land use changes provide plantations sizes remain stable.
  - *The yield is higher than that of corn at an average of 650 gallons per acre.*
  - Carbon dioxide emissions can be 90% lower than for conventional gasoline when land use changes do not occur.
- Disadvantages of sugar cane include:
  - Despite having a higher yield than corn, it is still relatively low
  - Few regions are suitable to cultivation
  - *Sugar cane is a food staple in countries of South and Central America*

SOYBEANS

- Unlike corn and sugar cane, soybeans are grown throughout much of North America, South America, and Asia. In other words, soybeans are a global food crop. The United States produce roughly **32%** of all soybeans in the world, followed by **Brazil at 28%.** Despite its relatively high price as a food crop, soybean is still a major feedstock for the production of biofuel. In this case, rather than ethanol, soybean is used to produce biodiesel. Soybean is probably the worst feedstock for biofuel production.
- Advantages of soybeans include:
  - Grows in many regions
  - Relatively easy to maintain
- Disadvantages of soybeans include:
  - A yield of only about *70 gallons of biodiesel per acre*, which is the worst yield of any crop. Palm oil produces almost 10 times as much biodiesel per acre at 600 gallons (note palm oil is considered a second generation feedstock).
  - Soybean is a common food source and thus its use as a biofuel directly threatens the food chain.
  - It faces a number of disease and pest burdens
  - It is generally not a profitable biofuel feedstock.
  - More energy is usually required to cultivate soybeans than can be derived from the fuel produced from them.

JATROPHA AND OTHER SEED CROPS

- In the early Part of the 21st century, a plant known as Jatropha became exceedingly popular
- The plant was praised for its yield per seed, which could return values as high as 40%. When compared to the 15% oil found in soybean, Jatropha look to be a miracle crop. Adding to its allure was the misconception that it could be grown on marginal land. As it turns out, oil production drops substantially when Jatropha is grown on marginal land. Interest in Jatropha has waned considerably in recent years.
- Other, similar seed crops have met with the same fate as Jatropha. Examples include Cammelina, Oil Palm, and rapeseed. In all cases, the initial benefits of the crops were quickly realized to be offset by the need to use crop land to achieve suitable yields.

2ND GENERATION BIOFUELS

- 2nd generation biofuels are produced from sustainable feedstock. The sustainability of a feedstock is defined by its availability, its impact on greenhouse gas emissions, its impact on land use, and by its potential to threaten the food supply.
- To qualify as a second generation, a feedstock must not be suitable for human consumption and
  - Should grow on marginal (non-agricultural) land
  - Should not require a great amount of water or fertilizer
  - Certain food products can become second generation fuels when they are no longer useful for consumption
    - *waste vegetable* oil (2nd generation feedstock)
    - Virgin vegetable oil (1st generation feedstock)
- Second generation biofuels are also referred to as "advanced biofuels"

SECOND GENERATION EXTRACTION TECHNOLOGY

- Because second generation biofuels are derived from different feed stock, Different technology is often used to extract energy from them.
- This does not mean that second generation biofuels cannot be burned directly as the biomass. In fact, several second generation biofuels, like *Switch grass*, are cultivated specifically to act as direct biomass.
- For the most part, second generation feedstock are processed differently than first generation biofuels. This is particularly true of *lignocellulose feedstock*, which tends to require several processing steps prior to being fermented (a first generation technology) into ethanol. An outline of second generation processing technologies follows:

THERMOCHEMICAL CONVERSION

- The first thermochemical route is known as ***gasification***. Gasification is not a new technology and has been used extensively on conventional fossil fuels for a number of years. Second generation gasification technologies have been slightly altered to accommodate the differences in biomass stock. Through gasification, carbon-based materials are converted to carbon monoxide, hydrogen, and carbon dioxide.
- This process is different from combustion in that oxygen is limited. The gas that result is referred to as synthesis gas or syngas. Syngas is then used to produce energy or heat. Wood, black liquor, brown liquor, and other feedstock are used in this process.

CONTINUED…

- The second thermochemical route is known as ***pyrolysis***. Pyrolysis also has a long history of use with fossil fuels. Pyrolysis is carried out in the absence of oxygen and often in the presence of an inert gas like halogen.
- The fuel is generally converted into two products: tars and char. Wood and a number of other energy crops can be used as feedstock to produce bio-oil through pyrolysis.

CONTINUED…

- A third thermochemical reaction, called ***torrefaction***, is very similar to pyrolysis, but is carried out at *lower temperatures*. The process tends to yield better fuels for further use in gasification or combustion.
- Torrefaction is often used to convert biomass feedstock into a form that is more easily transported and stored.

BIOCHEMICAL CONVERSION

- A number of biological and chemical processes are being adapted for the production of biofuel from second generation feedstock. Fermentation with unique or genetically modified bacteria is particularly popular for second generation feedstock like landfill gas and municipal waste.

WASTE VEGETABLE OIL (WVO)

- WVO have been used as a fuel for more than a century. In fact, some of the earliest diesel engines ran exclusively on vegetable oil. Waste vegetable oil is considered a second generation biofuels because its utility as a food has been expended. In fact, recycling it for fuel can help to improve its overall environmental impact.

Advantages of WVO are:

- It does not threaten the food chain
- It is readily available
- It is easy to convert to biodiesel
- It can be burned directly in some diesel engines
- It is low in sulfur
- There are no associated land use changes

Disadvantages of WVO are:

- *It can decrease engine life if not properly refined*
- WVO is probably one of the best sources of biodiesel and, as long as blending is all that is required, can meet much of the demand for biodiesel. Collecting it can be a problem though as it is distributed throughout the world in restaurants and homes.

NON-WOODY BIOMASS: GRASSES

A number of different grasses have been suggested as potential biofuel feedstock. The most commonly discussed is **Switchgrass**. Switchgrass has the potential to be used both directly and indirectly. Its *high cellulose conten*t makes it an ideal direct biomass. In some settings it is burned directly whereas in others it is mechanically converted into pellets for easy transportation and storage. As the ability to generate ethanol from cellulosic continue to advance, Switchgrass become a more and more attractive option for this as well.

- Benefits of switch grass over other biomass include:
  - Perennial (lowers costs)
  - Improved soil quality from not plowing each year
  - Relatively high yield on marginal land not suitable for food production
  - Drought and pest resistant
  - Low water and fertilizer needs

NON-WOODY BIOMASS: MUNICIPAL SOLID WASTE

- This refers to things like *landfill gas*, *human waste*, and *grass* and *yard clippings*. All of these sources of energy are, in many cases, simply being allowed to go to waste.
- Though not as clean as solar and wind, the carbon footprint of these fuels is much less than that of traditionally derived fossil fuels.
- Municipal solid waste is often used in cogeneration plants, where it is burned to produce both heat and electricity.

3RD GENERATION BIOFUELS

- Unofficial category reserved for biofuels derived from algae
- Previously, algae were considered second generation biofuels. However, when it became apparent that algae are capable of much higher yields with lower resource inputs than other feedstock, many suggested that they be moved to their own category
- Algae-based biofuels require a unique production mechanism and potentially offer solutions to mitigate most of the drawbacks of 1st and 2nd generation biofuels

POTENTIAL OF ALGAE-BASED BIOFUELS

- No feedstock can match algae In terms of quantity or diversity.
  - Algae produce an oil that can easily be refined into diesel or even certain components of gasoline
  - Algae can be genetically manipulated to produce everything from ethanol and butanol to even gasoline and diesel fuel directly
- Butanol is of great interest because the alcohol is exceptionally similar to gasoline. In fact, it has a nearly identical energy density to gasoline and an improved emissions profile.
  - Until the advent of genetically modified algae, scientists had a great deal of difficulty producing butanol
- Outstanding yields
  - Algae have been used to produce up to 9000 gallons of biofuel per acre, which is 10-fold what the best traditional feedstock have been able to generate
  - People who work closely with algae have suggested that yields as high as 20,000 gallons per acre are attainable
  - According to the US Department of Energy, yields that are 10 times higher than second generation biofuels mean that only 0.42% of the U.S. land area would be needed to generate enough biofuel to meet all of the U.S. needs.

TECHNIQUES FOR CULTIVATING ALGAE

Algae can adventitiously be cultivated in diverse ways:

- **Open ponds**

  Algae is grown in a pond in the open air

  - Simple design and low capital costs
  - Less efficient than other systems
  - Other organisms can contaminate the pond and potentially damage or kill the algae
- **Closed-loop systems**
  - Similar to open ponds but not exposed to the atmosphere and use of a sterile source of carbon dioxide
  - Could potentially be directly connected to carbon dioxide sources (such as smokestacks) and thus use the gas before it is every released into the atmosphere
- **Photobioreactors**
  - Complex, expensive, closed systems
  - Significantly higher yield and better control

CULTIVATING ALGAE

- For all three cultivation techniques, algae are able to be grown almost anywhere that temperatures are warm enough. This means that no farm land need be threatened by algae. Closed-loop and photobioreactor systems have even been used in desert settings.
- What is more, algae can be grown in waste water, which means they can offer secondary benefits by helping to digest municipal waste while avoiding taking up any additional land. All of the factors above combine to make algae easier to cultivate than traditional biofuels.

CHALLENGES OF ALGAE PRODUCTION

- Algae require large amounts of water, nitrogen and phosphorus to grow
  - So much in fact that the production of fertilizer to meet the needs of algae used to produce biofuel would produce more greenhouse gas emissions than were saved by using algae based biofuel to begin with.
  - It also means the cost of algae-base biofuel is much higher than fuel from other sources.
  - Currently, the net energy invested into producing biofuel using algae is greater than the amount of energy that can be extracted from the fuel
- This single disadvantage means that the large-scale implementation of algae to produce biofuel will not occur for a long time, if at all. In fact, after investing more than $600 million USD into research and development of algae, Exxon Mobil came to the conclusion in 2013 that algae-based biofuels will not be viable for at least 25 years. What is more, that calculation is strictly economical and does not consider the environmental impacts that have yet to be solved.
- A minor drawback regarding algae is that biofuel produced from them tends to be less stable than biodiesel produced from other sources. This is because the oil found in algae tends to be highly unsaturated. Unsaturated oils are more volatile, particularly at high temperatures, and thus more prone to degradation. Unlike the fertilizer requirements above, this is a problem that has a potential solution.

ADVANTAGES OF BIOFUELS

- They are renewable sources of energy unlike other natural resources like coal, petroleum and even nuclear fuel.
- Biofuels are the best way of reducing the emission of the greenhouse gases.
- Energy density: fossil fuels carry enough energy in a small enough space to make them very practical for a number of uses.
- Availability of Biofuels
- Environmental Impact

DISADVANTAGES OF BIOFUELS

- Regional Suitability
- Food Security
- Land Use Changes
- Impact on Biodiversity
- Global Warming

SUSTAINING BIODIVERSITY

- There is one last problem presented by biofuels that needs to be addressed: *biodiversity*. Biodiversity refers to the variety of different living things in an environment. For instance, if you grow only sweet corn in a field, you have low biodiversity. If, however, you grow sweet corn, dent corn, flint corn, flour corn, and popcorn, then you have high biodiversity. Why should we care?
- Growing a single type of corn is easier for producing biofuels because we can select that type that yields the best raw product, is easiest to grow, and which requires the least amount of water and other resources. This sounds great, but then down side to this is that pests that eat this type of corn will begin to proliferate. What is worse, if we spray with pesticide to kill these pests, some will inevitably be resistant to the pesticide. Over time, these pests will grow in number and we will be left with pests that are resistant to our chemical defenses. In the end, we have a bigger problem that what we started with and probably no corn because the new “super pest” ate it all.

CONTINUED…

- Biodiversity is important to ensuring that pests do not grow out of control. The type of farming needed to produce large quantities of biofuels is generally not amendable to high levels of biodiversity.
- This presents a fundamental problem in producing biofuels that is enhanced by the fact that "super pests" produced in the effort to grow biofuels can also threaten food crops.

LAND USE AND BIOFUELS

- The amount of land required to meet the world's energy needs using biofuels is a major concern. Depending on the feedstock, the requirements can be massive. The following numbers reflect the amount of land that would be needed to meet the requirements of just the global aviation industry.
  - Jatropha would need to be planted over 2.7 million square kilometers. That is an area roughly 1/3 the size of Australia.
  - Camelina would require an area of 2 million square kilometers.
  - Algae would need 68,000 square kilometers to meet the needs of the aviation industry. That is an area roughly the size of all of Ireland.
  - The aviation industry accounts for only 13% of all fuel consumption, so the values above would need to be increased 10-fold to encompass global fuel demand.
    - Jatraopha would need to be planted over 27 million square kilometers just to meet all fuel demands. An area that vast would cover all of Russia and the United States and still need a little more room.
    - Algae would require an area of 680,000 square kilometers, or all of France plus some.

CONTINUED…

- There is not enough land currently in use to meet fuel needs. That means forested areas would need to be cleared. This would release vast amounts of carbon and create a carbon debt that could take centuries to repay.
- The impacts of biofuels on greenhouse gas emissions were originally measured by considering only direct land use changes. When indirect land-use changes were considered, the greenhouse gas savings from biofuels increased as follows (note that negative and positive values are in comparison to current fossil fuels):
  - Corn ethanol â€“ From -20% to +93%
  - Cellulosic ethanol â€“ From -70% to +50%

AIR AND WATER CONCERNS WITH BIOFUELS

- Biofuels burn cleaner than fossil fuels, resulting in fewer tailpipe emissions of *greenhouse gases*, *particulate emissions*, and substances that cause acid rain such as sulfur.
- Biofuel production uses anywhere from 2 to 84 times as much water as fossil fuel production. Water use can be mitigated by planting crops that do not require irrigation.
- When the entire life cycle of a biofuel is considered, it may actually generate more greenhouse gases than fossil fuel. The following comparison of various fuel sources by *gram of carbon dioxide produced per megajoule of energy produced*. Note that the ranges provided for biofuels result from the location in which the feedstock is grown. For instance, sugarcane grown in Brazil as far less impact than sugarcane grown in South Africa.
  - Coal - 112
  - Gasoline - 85
  - Diesel fuel - 86
  - Natural gas - 62
  - Biofuel made from sugar cane 18-107
  - Biofuel made from wheat 58 - 98
  - Biofuel made from corn 49-103
- *Biodiesel is sulfur free, but contains nitrates that contribute to acid rain.*
- *Biodiesel has fewer polycyclic aromatic hydrocarbons, which have been linked to cancer.*

THE CARBON EQUATION

- Assuming we can overcome the problem of biofuels interrupting the food supply (such as growing algae in the ocean), can we overcome the problem of biofuels contributing to global warming? The answer, surprisingly, may be yes.
- It is true that biofuels produce carbon dioxide, which is a potent greenhouse gas and the one most often blamed for global warming. However, it is also true that growing plants consumes carbon dioxide. Thus, the equation becomes a simple balancing act. If the plants we grow utilize the same amount of carbon dioxide that we produce, then we will have a net increase of zero and no global warming. How realistic is this view?
- It may seem like a simple matter to only produce as much carbon dioxide as plants use. After all, couldn't we only burn biofuels and thus keep the equation balanced? Well, the math actually doesn't quite add up. Research has shown that energy must be invested into producing crops and converting them into biofuels before any energy is obtained. A 2005 study from Cornell University found that producing ethanol from corn used almost 30% more energy than it produced. In other words, you can't produce a perpetual motion machine using biofuels because you lose the energy you invest in creating them in the first place. In fact, you can't even break even.

CONTINUED…

- The other problem that we run into with biofuels is that carbon dioxide is not the only greenhouse gas we have to worry about. Other chemicals, like nitrous oxide, are also greenhouse gases and growing plants using fertilizer produces a lot of nitrous oxide. Basically, fertilizer contains nitrogen, which plants need to grow. However, most plants cannot convert molecular nitrogen into the elemental nitrogen they need. For this process, plants rely on bacteria.

  As it turns out, bacteria not only produce nitrogen that plants can use, they also produce nitrogen products like nitrous oxide, and probably more than was previously thought. The net result is that we may be balancing the CO_2 Â equation by using biofuels, but we are unbalancing the N_2O part of the equation and still causing global warming.

PROSPECTS FOR BIOFUEL

- A decade ago, subsidies for biofuel growth and development in many countries (especially the U.S.) were high.
- However, better understanding of global warming, increased awareness of the fragility of the food supply, and a general trend toward "greener" alternatives have all led to a decline in the popularity of biofuels.
- In 2011, The U.S. Senate voted 73 to 27 to end tax credits and trade protections for corn-based ethanol production. As the second largest producer of ethanol, this is a substantial move that reflects the changing pressures on our energy needs and shifted focus to environmentally friendly energy sources.

3. Recent Developments in Solar Drying systems

Overview of solar thermal integration concept applications

Level of Integration	Solar Thermal Integration Concept	Distinction	
Supply level	Parallel integration (direct or indirect) of solar heat	Heat Transfer Medium	Steam
	Heating of feedwater		
	Heating of make-up Water		
	Parallel integration (direct or indirect) of solar heat		Liquid
	Return flow boost		
	Heating of storages or cascades		
Process level	Heating of process medium	Conventional Way of Heating	External HEX
	Heating of intermediate hot water circuit		
	Heating of bath, machinery, or tanks		
	Heating of input streams		
	Solar heating with internal HEX		Internal HEX
	Vacuum steam		Steam Supply
	Low-pressure steam		

Reasons for implementing solar drying:

- Depletion of natural fuel resources
- Rising fossil fuel cost
- Environmental degradation
- Green- house gas emissions

Major challenges:

Intermittent nature of solar energy

Remedies:

Hybrid solar dryers

Energy Consumption: Industrial Drying

Industrial dryers consume a significant portion of the total energy used in manufacturing processes, which is **12% on the average**. For instance, the energy used in the drying industry was estimated to be **128×10^9 MJ/year** in selected UK areas. The overall pattern of energy consumption in some drying applications in France and the UK is illustrated in Table.

Table: Overall pattern of energy usage for drying

Subsector	French industry	British industry		% Due to drying
	Drying (10^9 MJ/year)	Drying (10^9 MJ/year)	Total (10^9 MJ/year)	
Food and agriculture	46.3[a]	35	286	12
Chemicals	8.6	23	390	6
Textiles	1.9[a]	7	128	5
Paper	38.8	45	137	33
Ceramic and building materials	15.7	14	127	11
Timber	7.9[a]	4	35	11
Others	50.3	No data	–	–
Total	≈ 168	128	1103	12

[a] Added thermal energy (tons of oil equivalent) and electricity (GWh), extracted from original data.

Textile Industry

Energy requirements for textile wet-processes

Product form/machine type	Process	Energy requirement (GJ/t output)
Desize unit	Desizing	1.0–3.5
Kier	Scouring/bleaching	6.0–7.5
J-box	Scouring	6.5–10.0
Open width range	Scouring/bleaching	3.0–7.0
Low energy steam purge	Scouring/bleaching	1.5–5.0
Jig/winch	Scouring	5.0–7.0
Jig/winch	Bleaching	3.0–6.5
Jig	Dyeing	1.5–7.0
Winch	Dyeing	6.0–17.0
Jet	Dyeing	3.5–16.0
Beam	Dyeing	7.5–12.5
Pad/batch	Dyeing	1.5–4.5
Continuous/thermosol	Dyeing	7.0–20.0
Rotary screen	Printing	2.5–8.5
Steam cylinders	Drying	2.5–4.5
Stenter	Drying	2.5–7.5
Stenter	Heat setting	4.0–9.0
Package/yarn	Preparation/dyeing (cotton)	5.0–18.0
Package/yarn	Preparation/dyeing (polyester)	9.0–12.5
Continuous hank	Scouring	3.0–5.0
Hank	Dyeing	10.0–16.0
Hank	Drying	4.5–6.5

Breakdown of thermal energy use in a drying plant in Japan

Item	Share of total thermal energy use (%)
Product heating	16.6
Product drying	17.2
Waste water loss	24.9
Heat released from equipment	12.3
Exhaust gas loss	9.3
Idling	3.7
Evaporation from liquid surfaces	4.7
Un-recovered condensate	4.1
Loss during condensate recovery	0.6
Others	6.6
Total	100

- As per IPCC, **global warming** is the most critical existent environmental issue.
- **Eco-efficiency** approach is adopted for restraining the emissions from overcoming this challenge.
- About **1/3rd** of the total global emissions are released by the **industrial sector**.
- Emissions raised by an average of **1.5%** each year during **1971-2004**.
- Considering all the environmental problems the requirement for the renewable energy source is unavoidable.

Renewable energy is a sustainable solution for the survival of humankind on this planet without depending on conventional resources

PRESENTATION OUTLINE: SOLAR DRYING

01 Introduction

02 Classification

03 Performance evaluation parameters

04 Advances in solar dryer

05 Applications of solar dryer

06 Previous studies on solar dryers

07 Recent studies on solar dryer

08 Published work on solar dryer in 2020 & 2021

SOLAR DRYING

The demand for food is predicted to rise by 40-50% by 2030 due to the increasing population. The post-harvest losses need to be reduced by using advanced food processing techniques. Solar drying is one such ancient technique of food preservation.

Various conventional techniques are used in food conservation like drying, refrigeration, salting, etc., but drying is particularly most significant for developing countries due to low investment of money and thermal processing facilities.

It helps in reducing the shortage of food by minimizing the agricultural losses occurring due to the presence of moisture content above the safe moisture limit. To reduce dependency on fossil fuels in the drying of agricultural products, solar energy must be used significantly for drying purposes

INTRODUCTION

Drying is a method of removing the moisture from the product up to its safe moisture limit. It is used for many centuries for food preservation. It gives microbiological stability and results in better quality products.

Rate of drying the products can be improved by controlling many factors such as solar radiation, humidity, wind velocity, etc.

Solar drying system preserves the food and agricultural products in the domestic and industrial sectors. It enhances the food usefulness, storage capacity, protection from environmental effects and reduces the cost of transportation.

INTRODUCTION

Open sun drying (OSD) is low in cost but it has a lot of disadvantages like deterioration in the quality of crops due to rain, dust, UV rays, etc. and also it is time-consuming.

Solar dryers were invented to overcome these limitations of OSD and improve the drying process. Solar dryers are more efficient for drying purposes and give more profit.

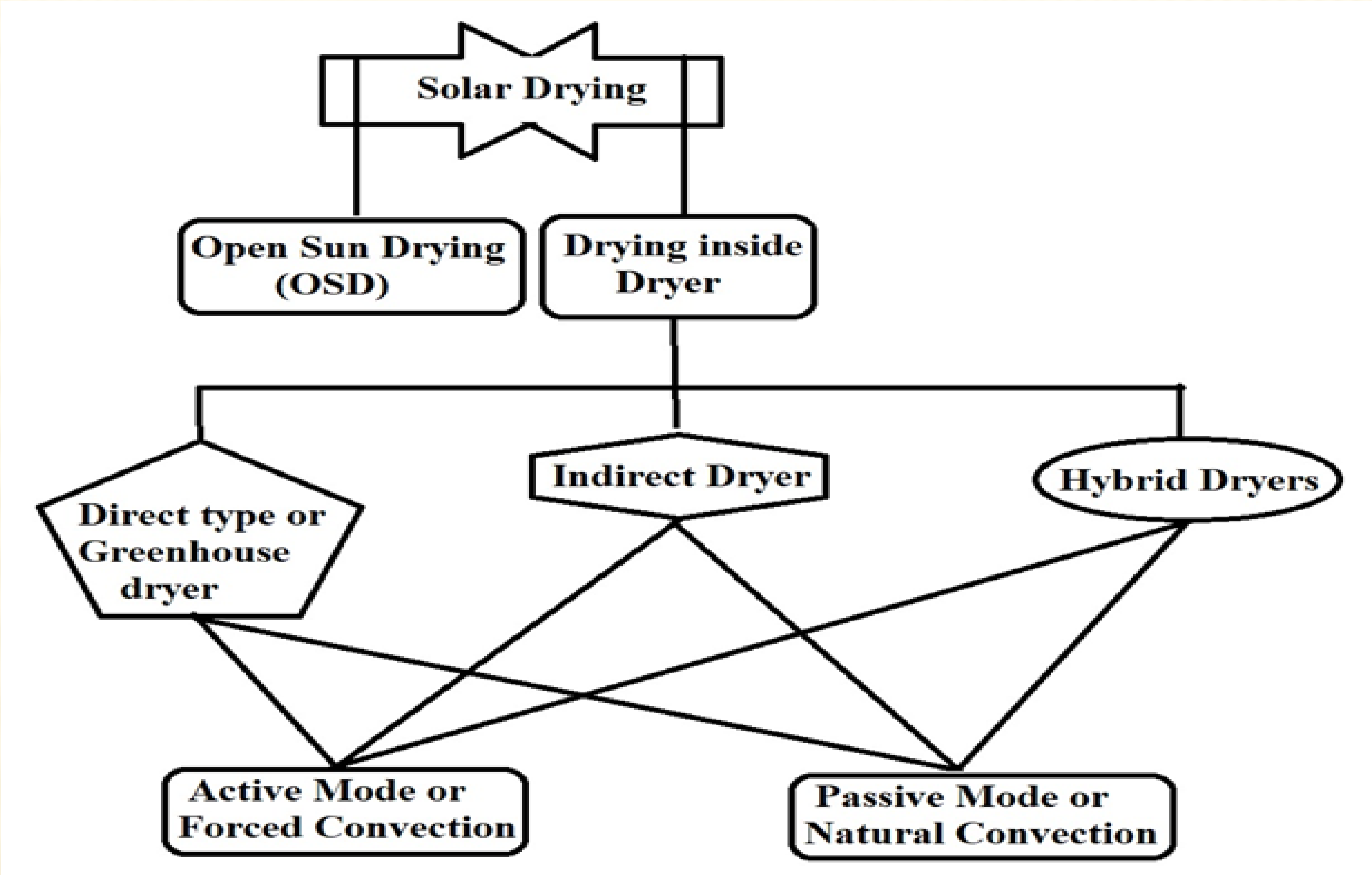
Dyers had been tested for drying various agricultural and non-agricultural produce.

Moisture content present in the various agricultural and non-agricultural products before and after drying with their drying time

Agricultural Products (Edible)			
Products	**Initial moisture**	**Final moisture**	**Drying Time**
Banana	68-70 % (wb)	20-24 % (wb)	4-5 days
Peeled Longan	81 % (wb)	12 % (wb)	3 days
Grapes	79.8 % (wb)	20.2 % (wb)	120 hrs
Carrot	7.76 g/g of dry matter	0.1 g/g of dry matter	220 min
Wild Ginger	80 % (wb)	8-11 % (wb)	27.5-30 days
Chillies	75 % (wb)	15 % (wb)	3 days
Coffee	52 % (wb)	13 % (wb)	2 days
Rice	37.5 % (wb)	15.5 % (wb)	3.39 hrs
Maize	33.3 % (db)	20 % (db)	1 day
Cassava	64.278 % (wb)	13 % (wb)	19 hrs
Mango	93.563 % (wb)	13 % (wb)	27 hrs
Pear	997.3 g	135.13 g	24 hrs
Amaranth grains	64 % (db)	7 % (db)	3.5 hrs
Pineapple Slices	85 % (wb)	10 % (wb)	72 hrs
Tomato	93.35 % (wb)	11.50 % (wb)	4 days
Turmeric	0.779 Kg/Kg dry matter	0.070 Kg/Kg dry matter	12 hrs
Cherry Tomatoes	62 % (wb)	15 % (wb)	4 days
Bitter Gourd	95 % (wb)	5 % (wb)	6 hrs
Fenugreek Leaves	88.5 % (wb)	7.3 % (wb)	18.75 hrs
Ghost Chilli Pepper	85.5 % (wb)	3 % (wb)	36 hrs
Ginger	86.3 % (wb)	3.5 % (wb)	30 hrs
Potato chips	80-83 % (wb)	8-9 % (wb)	6-7 hrs

Agricultural Products (Non-Edible)			
Products	**Initial moisture**	**Final moisture**	**Drying Time**
Seaweed	94.6 % (db)	10 % (db)	2 days
Red Seaweed	90 % (wb)	10 % (wb)	15 hrs
Lemon Balm Leaves	80 % (wb)	10 % (wb)	3.5 hrs
Olive Pomace	55 % (wb)	20 % (wb)	4 hrs
Jews Mellow	83 % (wb)	6 % (wb)	12 hrs
Mint Leaves	86 % (wb)	6 % (wb)	12 hrs
Valerina Jatamansi	89 % (wb)	9 % (wb)	120 hrs
Chamomile	72-75 % (wb)	6 % (wb)	30-33 hrs
Non-Agricultural Products			
Products	**Initial moisture**	**Final moisture**	**Drying Time**
Industrial Waste	68 % (wb)	11 % (wb)	8 hrs
Oil fronds	69 % (wb)	29 % (wb)	10-11 hrs
Papad	83 % (wb)	13 % (wb)	5 hrs
Jaggery	2 kg	1.75-1.8 kg	7 hrs
Fish	75 % (wb)	12 % (wb)	17 hrs
Rubber sheet	34.26 % (db)	0.34 % (db)	48 hrs
Gelidium Sesquipedale	2.043-2.58 % (db)	0.0668-0.0889 % (db)	--
Cocoon	60 % (wb)	12 % (wb)	16 hrs
Beef	309.39 % (db)	2.32-9.56 % (db)	11 hrs
Sludge	85 % (db)	6 % (db)	7-12 days

CLASSIFICATION



CLASSIFICATION

Solar drying is generally classified into two categories namely open or natural sun drying and closed sun drying.

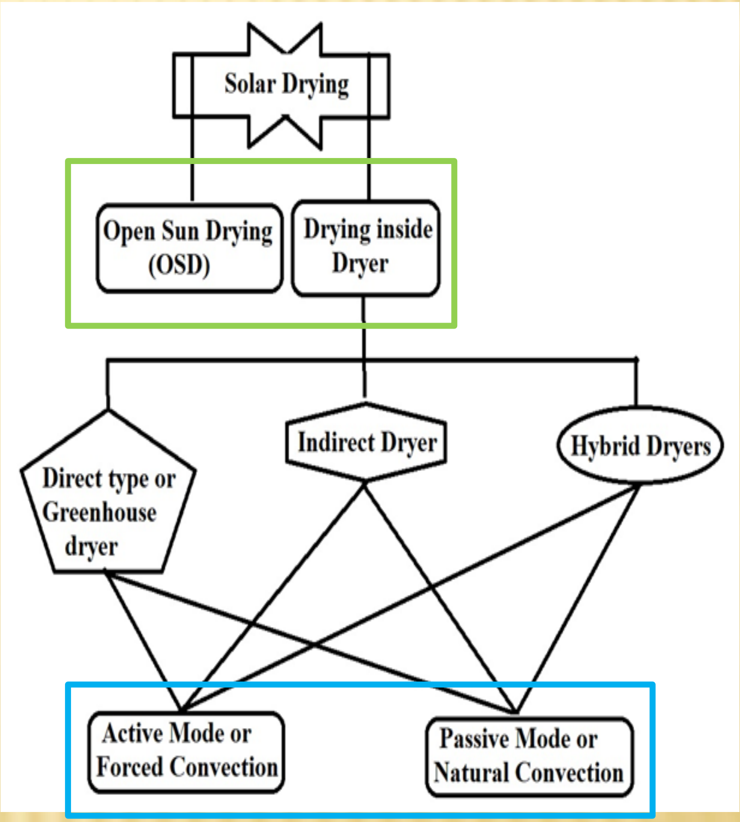
Natural sun drying

Closed sun drying

All the types of solar dryers operate in two modes only i.e. active and passive mode.

Active mode

Passive mode



PASSIVE V/S ACTIVE MODE

- **Passive dryers are suitable for low moisture content crops and less quantity while for high moisture content crops and large quantity, active dryers are preferred.**
- **As for drying a larger quantity of crop, the quantity and velocity of air should be sufficient to carry the moisture evaporated from the crop surface.**
- **Also, passive dryers are cheaper than active ones due to no external devices like fans, PV panels, blowers, etc.**

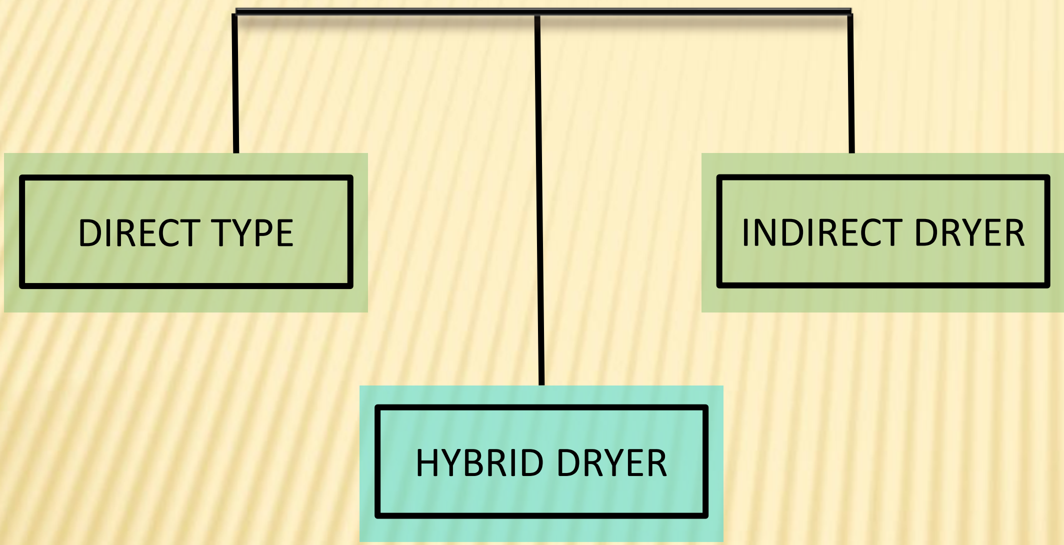
Drying of crops in passive greenhouse & the open sun

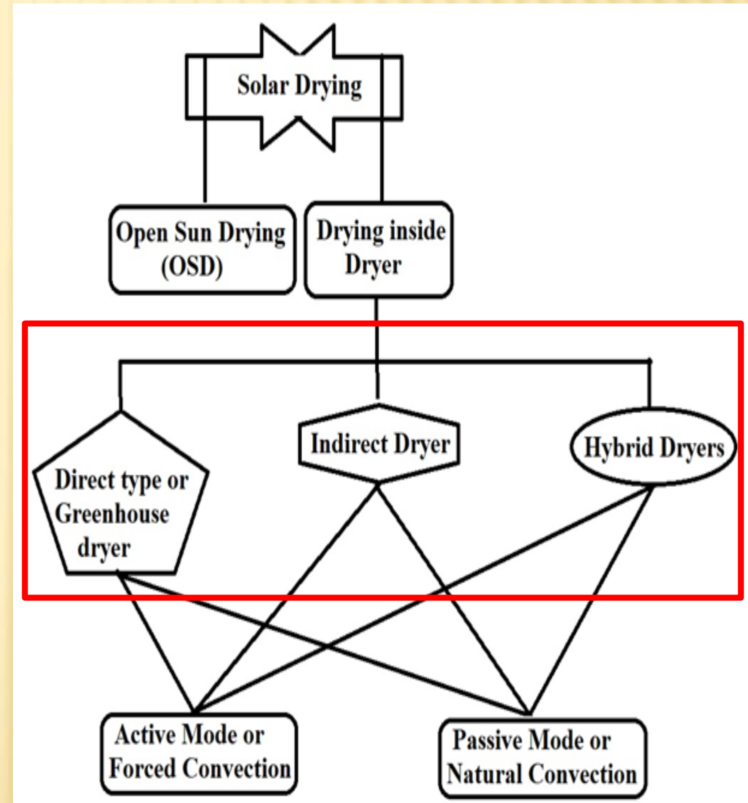
- **In passive mode, air flows through the crop by buoyancy force and with the help of wind pressure.**
- **In active mode, the crop is dried with the help of forced circulation generated by a fan or blower operated by electrical energy. This requirement is fulfilled either by the PV module or grid energy.**

Setup of greenhouse dryer operating under active mode

CLASSIFICATION

Types of solar dryer





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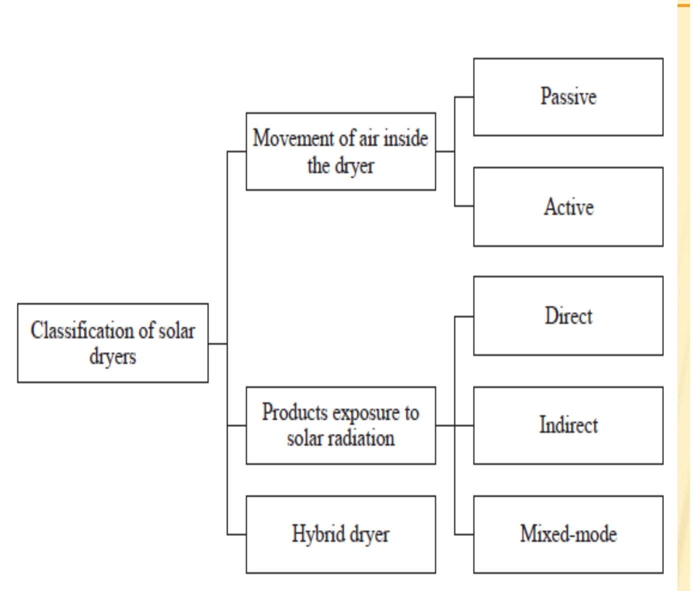
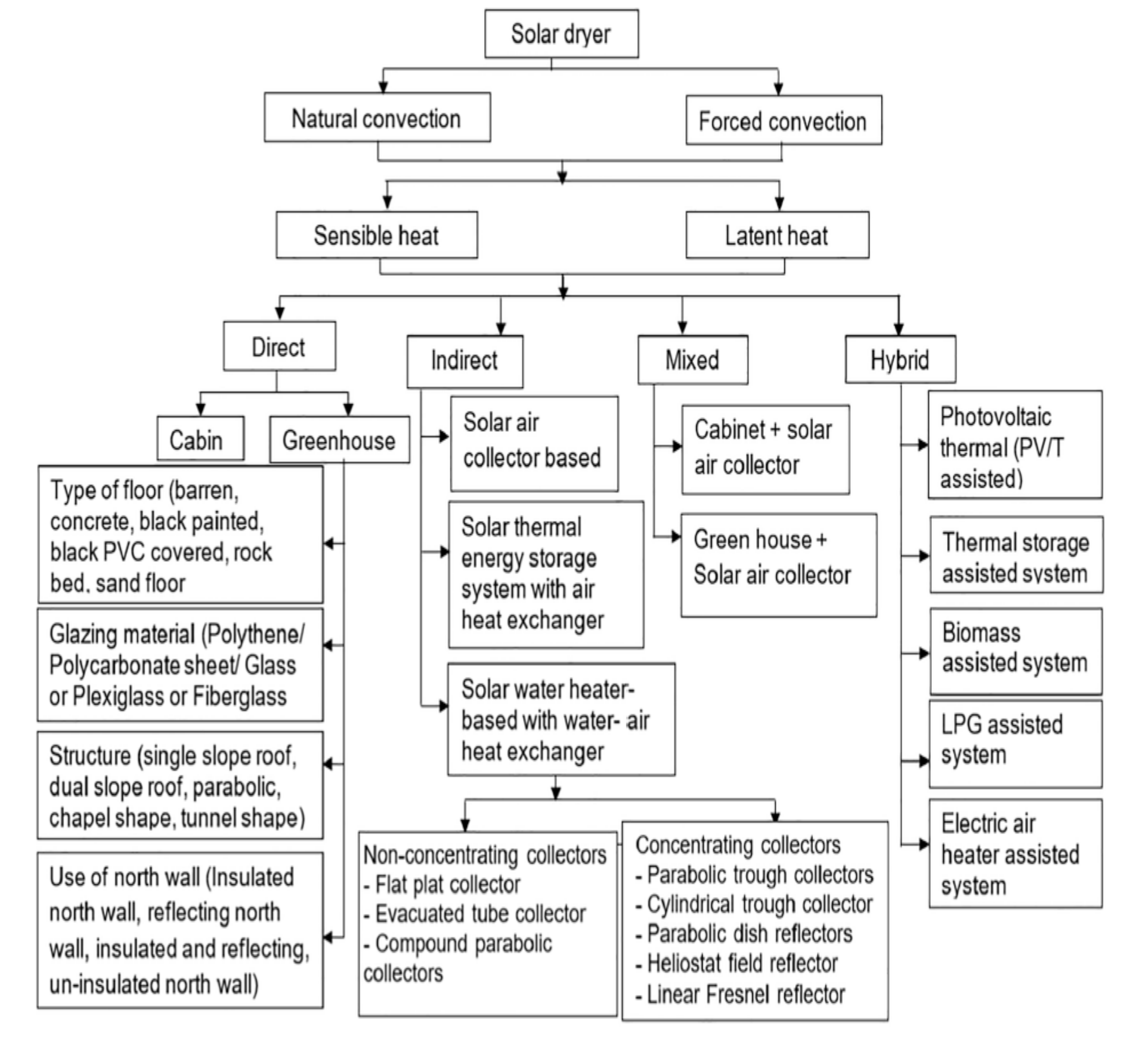
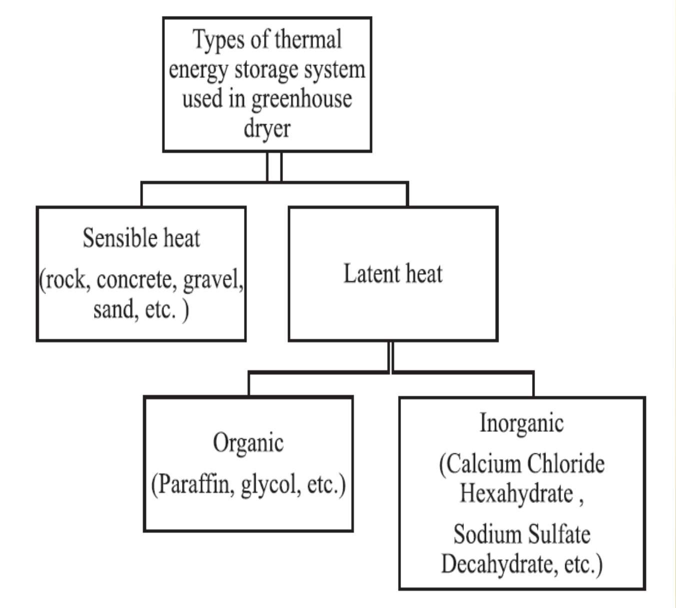
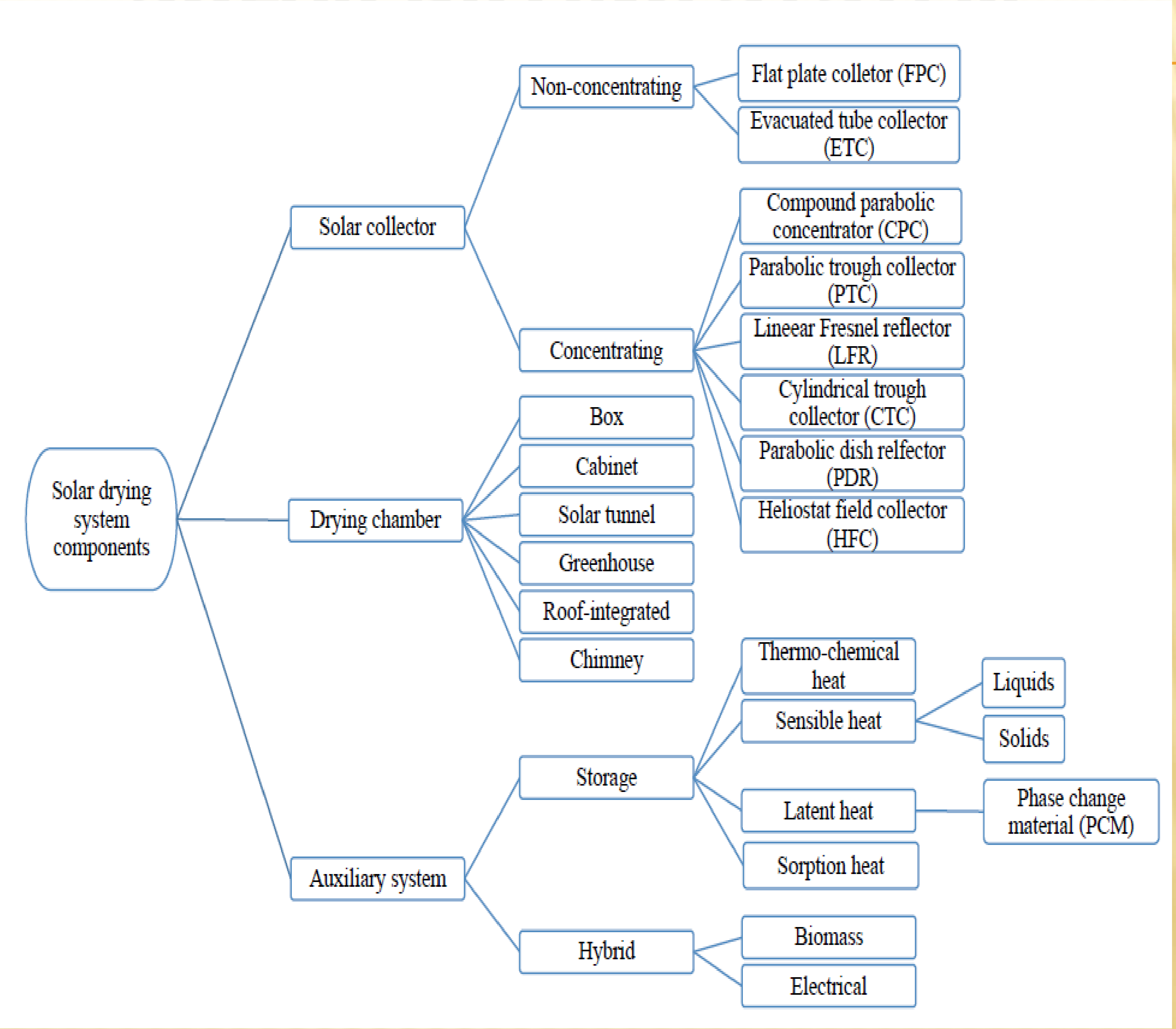




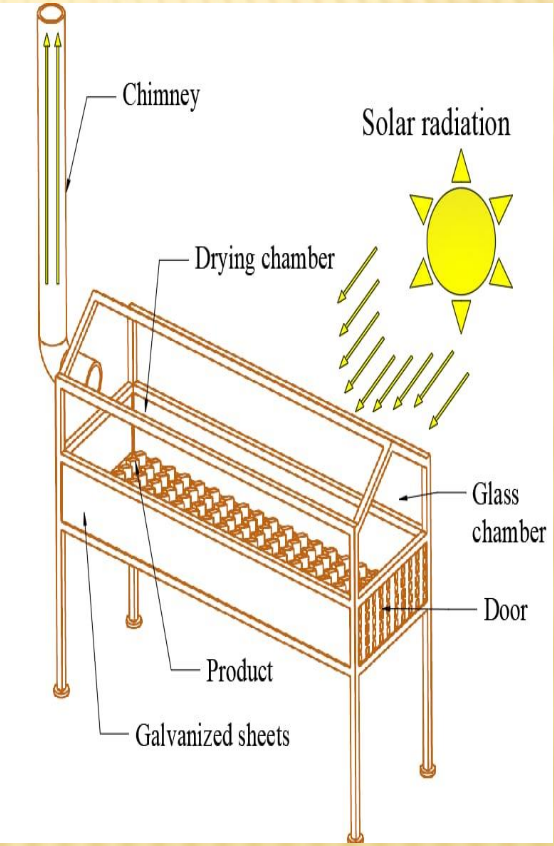


SOLAR DRYING SYSTEM



DIRECT SOLAR DRYERS

- In direct mode, the solar radiation is utilized directly for drying the crops kept inside the drying chamber.
- It is covered with some transparent material like glass, polyethylene sheet, etc.
- Some part of the radiation is absorbed and transmitted by the covering material while some of it gets reflected
- The solar insolation transmitted inside the chamber gets trapped and raises the inside temperature of the dryer.
- Due to increased room temperature, the moisture of the crop starts evaporating from the surface of the crop.



Schematic view of Direct type solar

SOME OF THE RESEARCHES CARRIED OUT ON DIRECT TYPE SOLAR DRYERS IN RECENT YEARS

ACTIVE MODE

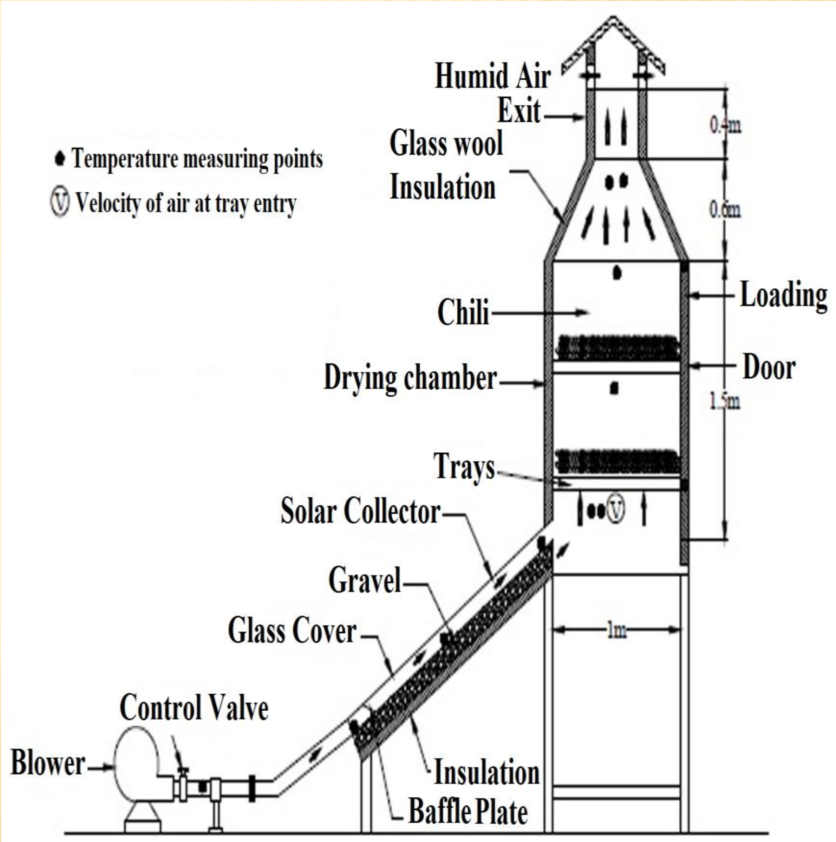
S.NO	AUTHOR	YEAR	CROPS DRIED	OUTCOME/OBSERVATION
1.	Malakar et. al.	2021	Garlic clove	Garlic cloves (10 kg) were dried from 69% to 8% moisture content (wb). The maximum drying rate, solar collector efficiency, and dryer efficiency were found to be 1.56 kg H_2O/kg dry solid/h, 45.86%, and 56% respectively at 2 m/s air flow velocity. The highest average exergy efficiency of 56.59% was found at 2 m/s, and the average lowest exergy loss of 4.74 W was found at 1 m/s.
2.	Mewa E.A. et al.	2019	Beef	Drying kinetics of beef drying was evaluated and drying data were fitted into five drying models. The beef was dried from 20 kg to 7.5 kg in 11 hrs. Page model fits best for the drying behavior of beef.
3.	Tellez et al.	2018	Stevia leaves	Tone degradation of the samples was highly dependent on the temperature of the drying air. Discoloration of samples was found lesser.
4.	Morad M.M. et al.	2017	Peppermint plants	Three identical tunnel dryers were developed and tested with different conditions namely different load, different plant conditions and different air flow rates. Continuous fan operating condition increases the drying rate by 22.78% as compared to periodical operating condition but overall cost also increases in this case.
5.	Sahdev R.K. et al.	2016	Groundnut	Calculated the convective heat transfer coefficient (hc) for the groundnut drying in the greenhouse dryer with different tray size conditions. It was found that the value of hc decreases with the increase in the size of the tray.
6.	Prakash Om, Kumar A, and Laguri V.	2016	Tomato, capsicum, and potato	Uses thermal storage material in a modified greenhouse dryer. The nutritious value of the dried product inside the dryer was found more than the nutritious value in the open sun. The energy and cost analysis in three different floor conditions and with three different crops had been carried out. The dryer emits 13.45 kg $C0_2$ in passive mode and 17.60 kg $C0_2$ in active mode per year.
7.	Y.I. Sallam et al.	2015	Mint	Developed two identical direct and indirect dryers operating both on active and passive mode. The faster drying was observed in the case of active drying. drying behavior in both modes was tested by a curve fitting method of 10 thin layer drying models.

Some of the researches carried out on direct type solar dryers in recent years

Passive Mode				
S.NO.	Author	Year	Crops Dried	Outcome/Observation
1.	Kumar et al.	2019	Groundnut	The effect of sieve size on the value of he and hc was evaluated for the greenhouse drying of groundnuts. It was found that the value of both the heat transfer coefficient decreases with the increase in the sieve size.
2.	Mennouche et al.	2014	Deglet nour dates	Direct solar dryer with chimney was developed to dry hard deglet nour dates. The dryer was tested with three different conditions and found that in combination mode i.e. in passive mode with shades gives good results in terms of quality with less drying time. In natural mode, the drying time was 2.60 hours while in combination mode the drying time was 8 hours but with better quality product.
3.	Prakash and Kumar	2014	Jaggery	ANFIS model was used to predict the jaggery temperature, greenhouse temperature, and mass of jaggery during drying. Experimental analysis shows that ANFIS is better than thermal modeling. The correlation coefficient was 0.99-1.00 in the case of ANFIS while it lies between 0.9-0.98 in the case of thermal modeling.
4.	Mustapha et al.	2014	Fish	Constructed five dryers of different materials namely glass, mosquito net, aluminum, plastic, and Glass with black stones. The results obtained from these dryers were compared with smoking kiln and oven data. Reported that solar dryers can be useful for less payback periods and low cost and better quality.
5.	B. Ringeisen et al.	2014	Tomatoes	The dryer was integrated with a curved concentrator for focusing solar radiation on the tomatoes. Due to this, the drying time was reduced by 21%.

INDIRECT TYPE SOLAR DRYER

- Indirect solar dryer receives solar radiation in the solar collector for heating the air externally and transfers the hot air to the opaque drying cabinet.
- The advantage of indirect dryers over direct dryers is that the higher temperature can be maintained inside the drying chamber.
- As air is heated in the solar collector and then it is supplied to the drying cabinet, which is properly insulated.
- So heat loss in the cabinet reduces and a higher temperature is obtained.
- High temperature reduces the drying time but also it compromises with quality and texture.



Indirect forced convection solar dryer

SOME OF THE RESEARCHES CARRIED OUT ON INDIRECT TYPE SOLAR DRYERS IN RECENT YEARS

ACTIVE MODE				
S.NO	AUTHOR	YEAR	CROPS DRIED	OUTCOME/OBSERVATION
1.	Singh et al.	2021	Fenugreek leaves	Thermal efficiency of the solar dryer was 34.1% and 5.7% for the OSD. Ascorbic acid, total chlorophyll content, and color were better in the solar dryer. Payback period was 604 drying days.
2.	Hidar et al.	2020	Stevia leaves	Effective moisture diffusivity varied from 5.07×10^{-11} and 3.14×10^{-10} $m^2\ s^{-1}$. Activation energy reported as 37.81 kJ/mol. Total phenolic, flavonoids, and chlorophyll content decreased with the increase of air temperature
3.	Etim P.J. et al.	2020	Banana	Investigated the effect of air inlet shape and size on drying kinetics. The dryer efficiency was maximum for inlet of triangular-shaped having 20 cm^2 area.
4.	Bhardwaj A.K. et al.	2019	Valerina Jatamansi	The dryer was attached with sensible heat storage as well as phase change materials for absorbing solar radiations in the Himalayan region. The medicinal herb herb was dried from 89% moisture content to 9% in 120 hours. The energy efficiency of the collector increases by 16.12% after using sensible heat storage material with a solar collector attached to the dryer.
5.	S. Shamekhi-Amiri et al.	2018	Lemon Balm leaves	The dryer attached with a double pass solar collector was developed and tested with different air flow rates. The optimum air flow rate for the developed setup was 0.006125 m^3/s. At this flow rate, the balm leaves were dried from 80% moisture to 10% in 3.5 hours.
6.	Sansaniwal S.K. et al.	2017	Ginger rhizomes	The drying behavior of the developed dryer was tested in terms of convective heat transfer coefficient and collector efficiency for natural as well as forced mode. As the value of h and collector efficiency was reported higher in the forced mode so they suggested that for high moisture crops, the forced convection gives better results.

SOME OF THE RESEARCHES CARRIED OUT ON INDIRECT TYPE SOLAR DRYERS IN RECENT YEARS

Passive Mode				
S.NO.	Author	Year	Crops Dried	Outcome/Observation
1.	Zoukit A. et al.	2019	No-load	Uses the Takagi-Sugeno fuzzy model for predicting the inside temperature of the dryer under active as well as in passive mode. It was found that the TSF model not only reduces the simulation time but also gives better prediction than other methods.
2.	Essalhi H. et al.	2018	Grapes	Studied the drying characteristic of the indirect dryer with the thermal energy storage method. The dryer was attached with a solar collector having corrugated aluminum plates for absorbing more thermal energy. Midilli et al. model give the best fit amongst the 10 models tested for drying behavior of grapes. In 120 hours duration, the moisture is reduced to 20% on a wet basis.
3.	Essalhi H. et al.	2017	Pear	The absorber of solar collector consists of two corrugated aluminum plates. The efficiency of the indirect dryer was 11.11%. In 24 hours, 0.86 Kg of water was removed from the pears. The maximum temperature of air coming out of the collector was 57°C.
4.	Sansaniwal and Kumar	2015	Ginger	Tested the dryer in passive mode by drying ginger inside it. The modified page model was fitted best with the experimental drying rate.
5.	S. Maiti et al.	2011	Papad	Developed the dryer attached with collectors having two reflectors. For the collector area of 1.8 m^2, the dryer removes moisture content from 83% to 12% in drying time of 5 hours. The dryer efficiency was 13% when it is loaded fully.

MIXED-MODE OR HYBRID DRYERS

- A mixed-mode dryer is developed for a faster drying rate. It is a combination of both direct and indirect types of solar dryers. In such a dryer, solar radiation is absorbed in both flat plate air collectors as well as in the drying chamber
- Mostly the hybrid dryer operates on active mode. The DC fan or blower should be provided to maintain air circulation. In PVT hybrid dryers the fan is operated by electricity generated by PV modules
- Hybrid dryer utilizes two sources of energy, one is solar and other may be biomass, LPG, or any other source that can be able to supply hot air during off-sunshine hours.

Setup of PVT mixed-mode dryer

- *For commercial scale, the hybrid dryers are preferred as they are standalone dryers and able to supply the heat required by a large quantity of products to evaporate moisture from them.*
- *As in hybrid dryers, more devices are attached so the embodied energy of the dryer increases, and hence the net CO_2 emission from the dryer also increases.*
- *Also, the hybrid dryers are more costly than other types of the dryer but performance-wise these are better than other types.*

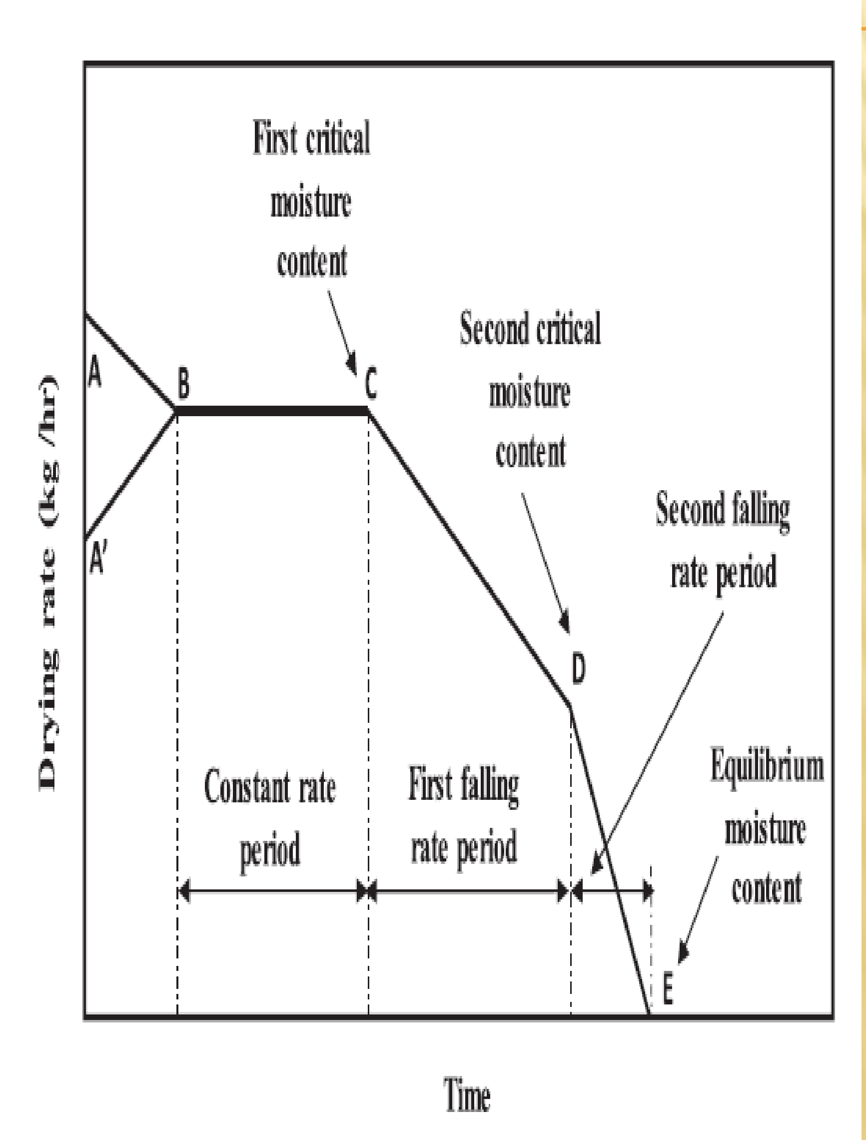
SOME OF THE RESEARCHES CARRIED OUT ON HYBRID TYPE SOLAR DRYERS IN RECENT YEARS

S.NO.	Author	Year	Crops Dried	Outcome/Observation
1.	Ekka and Palanisamy	2020	Red Chilli	Evaluated the convective heat transfer coefficient of the red chili by drying it inside the mixed-mode dryer with thermal energy storage. It was concluded that h_e is an important parameter affecting the moisture evaporation rate and its value increase with an increase in air temperature inside the dryer.
2.	Hamdi I. et al.	2019	Red Pepper	Studied the drying behavior of red pepper in the greenhouse dryer by fitting the drying curve in eight different models. The drying time was shortened by 7 hours in the dryer as compared to OSD. The overall drying efficiency was 34% and the payback time of the dryer was 1.02 years.
3.	Hamdi et al.	2018	Grapes	Developed the mathematical models for drying kinetics of grapes in a chapel shaped greenhouse attached with flat plate collector. The grapes were dried from 5.5 g water/g dry matter to 0.22 g water/g dry matter in 128 hours.
4.	Karthikeyan and Murugavelh	2018	Turmeric	The dryer covered with a polycarbonate sheet was attached with a flat plate collector. The maximum temperature at the inlet of the drying chamber was 82.8°C. The energy and exergy analysis of the dryer was also carried out and the average exergy efficiency of the dryer was 49.12%. The model for calculating the drying rate of the turmeric was also developed.
5.	Hamdani et al.	2018	Fish	The direct type of dryer was developed for fish drying. The dryer was coupled with a biomass burner and a cross-flow heat exchanger. The maximum temperature inside the dryer was 50°C. In 17 hours the moisture content has been reduced from 75% to 12%.

STAGES OF DRYING PROCESS

Lines **A’B** and **AB** represent the **Warming-up Period** or initial adjustment period. During this period, the temperature of the product increases due to the supply of heat energy, and subsequently, the product surface is cooled due to the evaporation of moisture content. The heating and subsequent cooling of the product gets stabilized after a time period, and the temperature of the product remains constant.

Line **BC** represents the **Constant Drying Period** and during this period, a constant rate of evaporation per unit surface area takes place. Constant drying rate occurs when the water at the surface of the products gets evaporated, and it gets replaced by the migration of the water molecules from the product to the surface. Constant drying rate is not exhibited in organic products. Point **C** represents the end of the constant rate drying period, and it is called **First Critical Moisture Content.**

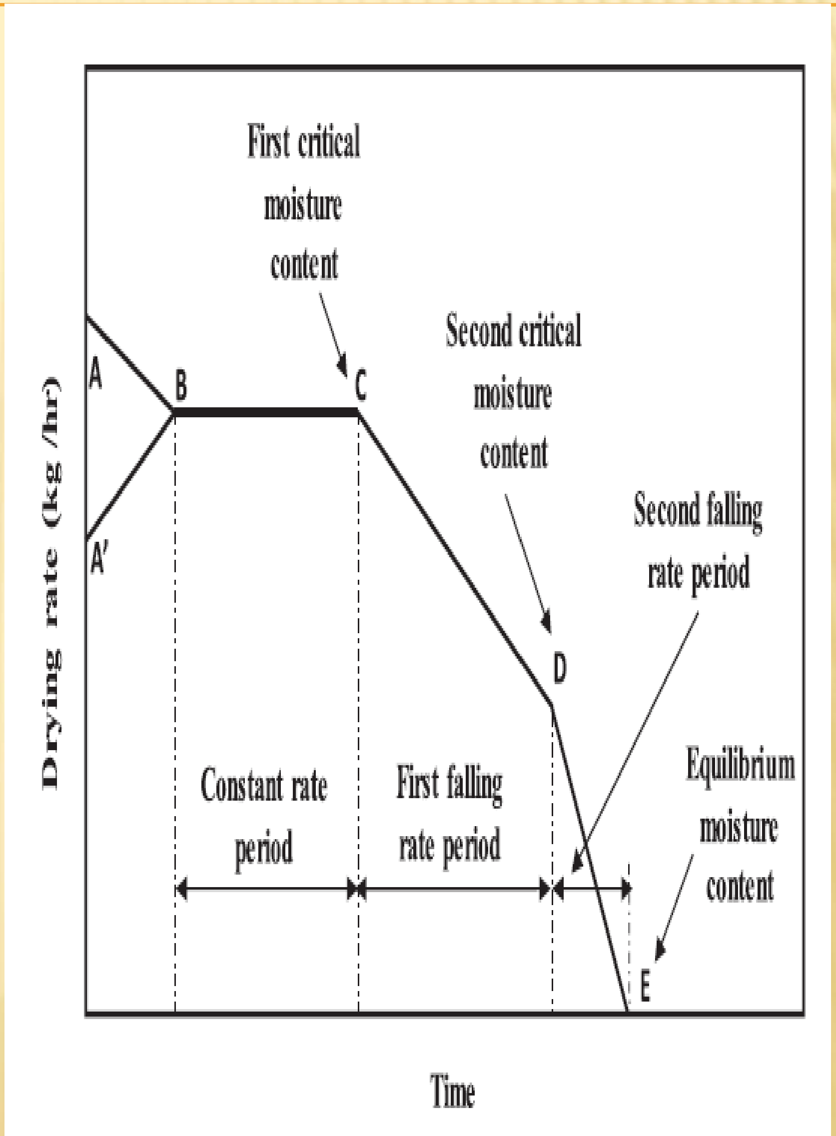


STAGES OF DRYING PROCESS

Line **CD** represents the **First Falling Rate Period**. Falling rate period occurs when the water at the surface is depleted, and the capillary force stops the migration of water to the surface, and hence the moisture diffusion is controlled by the internal liquid movement within the product. During this period, the drying rate reduces continuously.

Point **D** represents the **Second Critical Moisture Content**, and line DE represents the second falling rate period during which the drying rate reduces rapidly.

Point **E** represents the **Equilibrium Moisture Content**. It is the limiting moisture content level below which a product cannot be dried.



PERFORMANCE EVALUATION PARAMETERS OF SOLAR DRYER

- Performance of solar dryers depends on various factors such as moisture content, drying period, dryer efficiency, etc.
- Different types of solar dryers have different parameters which affect their performance, as given:

For Direct Solar Dryer

- **Moisture Content (M_C):** The quantity of water present in a material, such as fruits, is known as moisture content or water content. The moisture content in percentage can be determined using the following relation:

$$M_c = \frac{M_i - M_d}{M_i} \text{ x } 100$$

M_i is mass of food product before drying, M_d is mass of food product after drying

- **Moisture Ratio (MR):** The moisture ratio of the food product is calculated by using equilibrium moisture content and initial moisture content. The relation of the moisture ratio is given as:

$$MR = \frac{M - Me}{M_O - M_e}$$

M is moisture content at any time, M_e is equilibrium moisture content, M_o is initial moisture content of the food material

Performance evaluation parameters of solar dryer

For Direct Solar Dryer

- **Drying Rate (R_d):** Drying rate is indicated using the graphical representation with time and moisture content as its coordinates. The drying rate is determined as:

$$R_d = \frac{M_i - M_d}{t}$$

where,
t is time interval of readings taken during the drying period

- **Drying Efficiency:** The ratio of total heat consumed by the product for evaporating the moisture present inside it to the total amount of solar radiation on the collector surface is known as drying efficiency, and calculated as;

$$\eta_d = \frac{W \times \Delta H_1}{A_C \times I_C}$$

where,
W is moisture evaporated from food product (kg)
ΔH_1 is latent heat of vaporization of water (2320 kJ/kg)
I_c is total hourly isolation upon collector (Wm^2)
A_c area of the collector, (m^2)

Performance evaluation parameters of solar dryer

For Indirect Solar Dryer

- **Drying Period:**
  - It is the duration during which drying of the food product is carried out inside the dryer.
  - The drying time is taken into estimation from the time when the food product is kept in the dryer until when it dries to a certain moisture content level.
  - The drying period is estimated in hours or days.

- **Flow Velocity of Air:**
  - It is the velocity of air (in m/s) which is provided inside the drying chamber by active (forced flow) or passive (natural flow) medium.
  - In active indirect type solar dryer, the food product is dried in higher air velocity than passive indirect type solar dryer.

- **Dryer Efficiency:** The dryer efficiency gives the performance of the dryer. It shows that how effectively the energy input is used to dry the food product. Dryer efficiency is given as;

$$\eta_{dryer} = \frac{M \times L}{I_C \times A \times t}$$

L is latent heat of vaporization of water, M is mass of food material, t is drying period.

Performance evaluation parameters of solar dryer

For Indirect Solar Dryer

- **Collector Efficiency (η):**
  - The collector efficiency is described by conversion of sun's radiation into usable heat gain and losses.
  - The heat gain and losses are calculated by performing thermal analysis.
  - The relation for collector efficiency is;

$$\eta = \frac{\rho \times V \times C_P \times \Delta T}{A \times I_C}$$

where,

ρ is air density (kg/m^3)

I_c is insolation on the collector

ΔT is difference of temperature (K)

C_p is specific heat capacity of air at constant pressure (J/kgK)

V is volumetric flow rate (m^3/s)

A is collector's effective area facing the sun (m^3)

Performance evaluation parameters of solar dryer

For Mixed Mode Solar Dryer

- **Pressure Drop Calculation:** The pressure drop is defined as the difference in pressure between two points of a fluid carrying network. The pressure drop across the orifice plate has measured by the following relationship;

$$\Delta P_O = \Delta h \times 9.81 \times \rho_m \times \frac{1}{5}$$

ΔP_o is pressure difference,
Δh is difference of liquid head in manometer
ρ_m is density of mercury, 13.6×10^3

- **Mass Flow Measurement:** Mass flow rate of air is the mass of airflow per unit of time, and it is calculated by measuring pressure difference across the orifice plate by following relation;

$$m = C_d \times A_O \times \left[\frac{2\times \rho \times \Delta P_O}{1-\beta^4}\right]^{0.5}$$

where,
m is mass flow rate of air (kg/s)
C_d is coefficient of discharge of orifice (0.62)
A_o is area of orifice plate in (m^2)
ρ is density of air (1.157 kg/m^3)
β is ratio of diameter (D_o/D_p)

Performance evaluation parameters of solar dryer

For Mixed Mode Solar Dryer

- **Reynolds Number:** Reynolds number is determined as the ratio of viscous force and inertia force, and given as;

$$R_e = \frac{VD}{\upsilon}$$

Where,
V is air velocity (m/s)
D is hydraulic diameter (m)
υ is kinematic viscosity 16.70×10^{-6} (m^2/s)

- **Heat Gained by Air:** The heat gained by the air is calculated using inlet and outlet temperature of the air. The heat transfer rate inside solar air heat collector is given by;

$$Q_a = m \times C_P \times (T_O - T_i)$$

Where,
m is mass flow rate of air (kg/s)
C_p is specific heat of air (kJ/kg)
T_o is outlet temperature (°C)
T_i is inlet temperature (°C)

Performance evaluation parameters of solar dryer

For Mixed Mode Solar Dryer

- **Thermal Efficiency:** It is the ratio of heat gained by the air inside collector to the product of the area of collector and solar insolation. It is a dimensionless parameter. The thermal efficiency of a mixed mode dryer is given as;

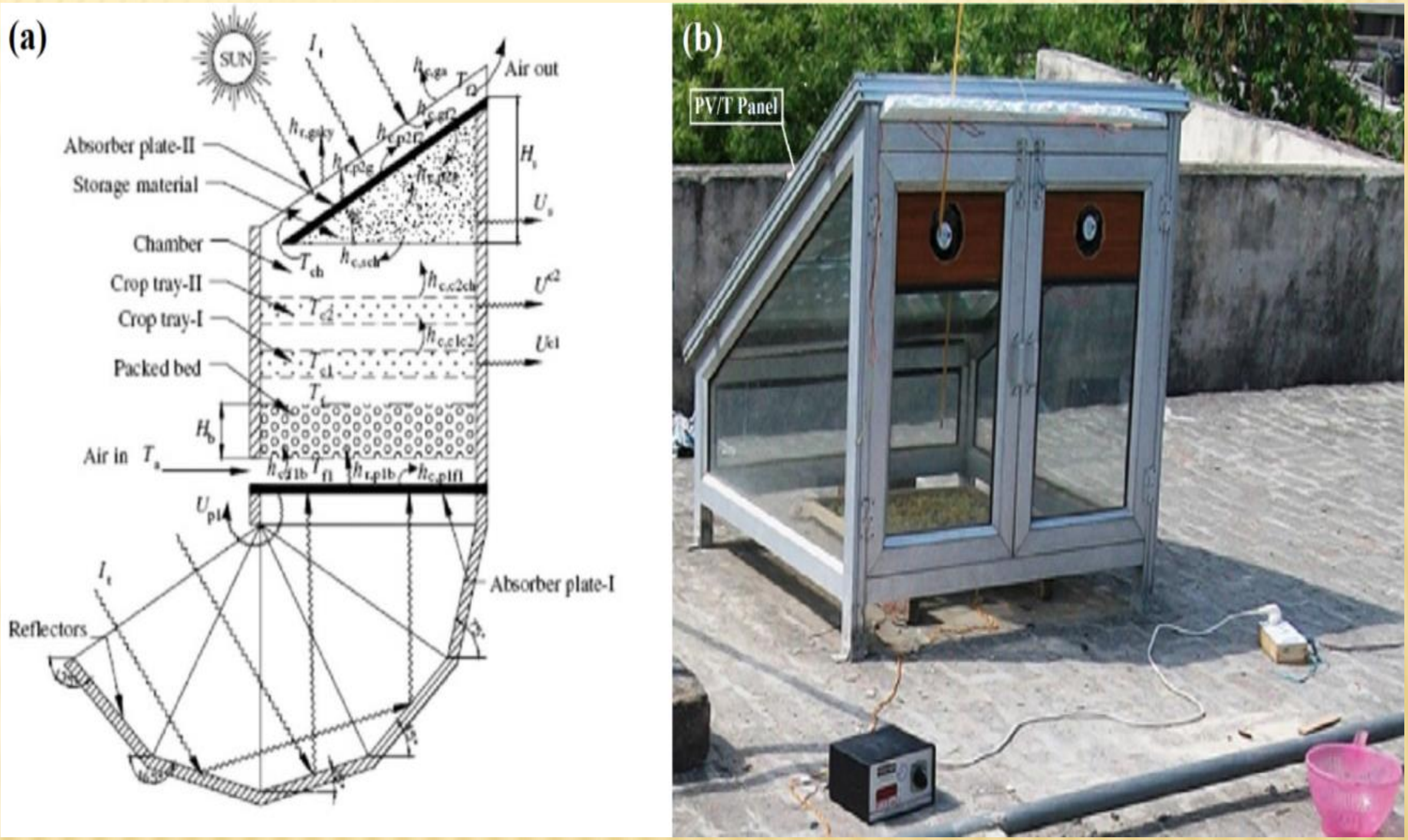
$$\eta = \frac{Q_a}{I \times A_P}$$

Where,
Q_a is heat gain by air (watts)
A_p is area of collector plate (m^2)
I is solar insolation (W/m^2)

ADVANCES IN SOLAR DRYER

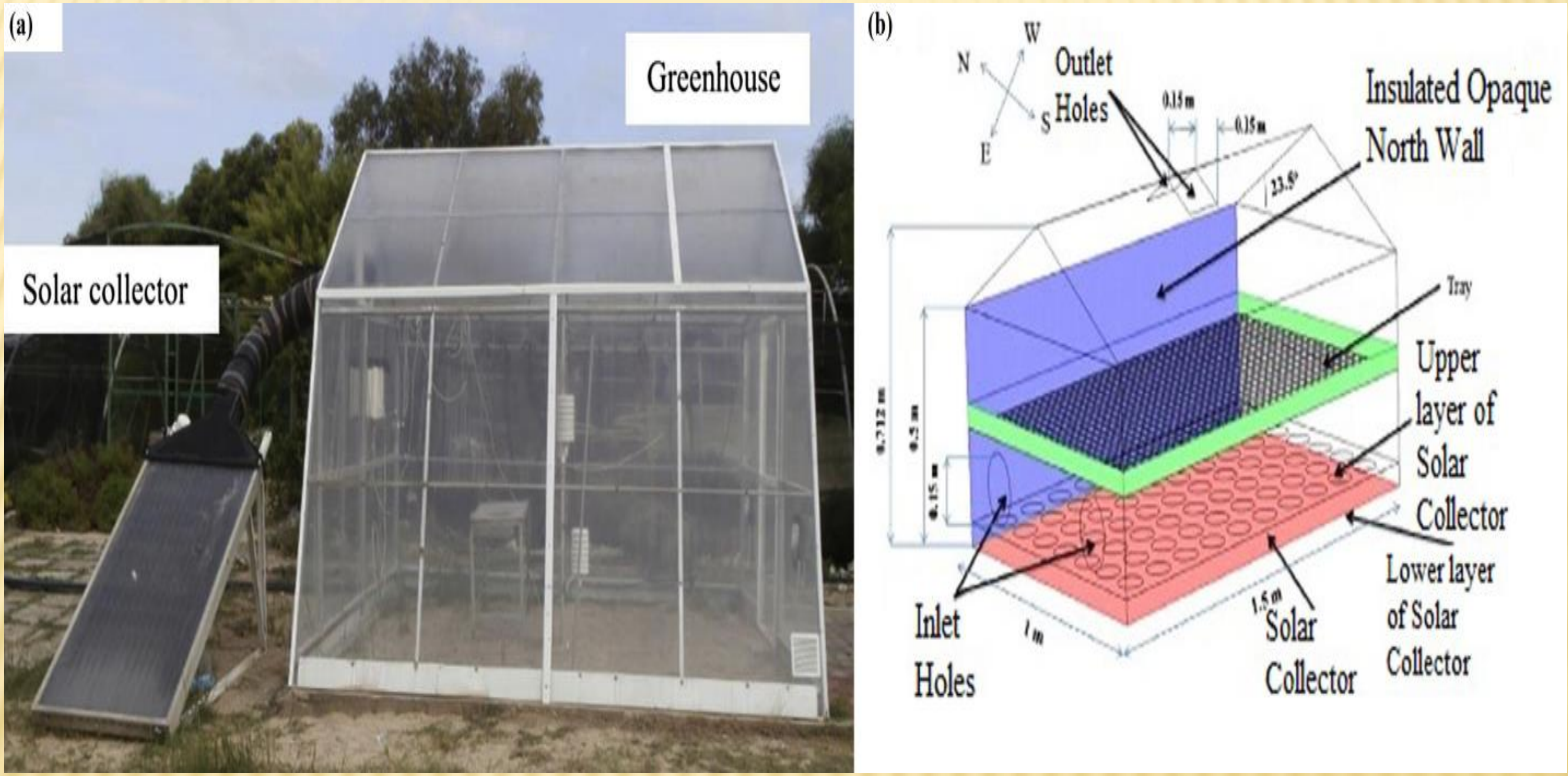
- Solar dryers are tried to make more efficient by overcoming their limitations.
- One of the limitations of solar drying is that it can't be used in off sun-shine periods and also the intensity of solar radiation is not the same at all places.
- But this problem can be overcome by storing the thermal energy of solar radiation in form of sensible or latent heat .
- During sensible heating, the temperature of the material increases and thus storing the heat energy and releases this energy when required.
- The heat stored in the material depends on the temperature difference and specific heat.
- A latent heat storage system is another method of storing thermal energy in dryers and is based on the absorption or rejection of latent heat at a constant temperature.
- In this system storage material changes its phase from solid to liquid, liquid to gas or vice versa hence phase change materials are used in a latent heat storage system

ADVANCES IN SOLAR DRYER



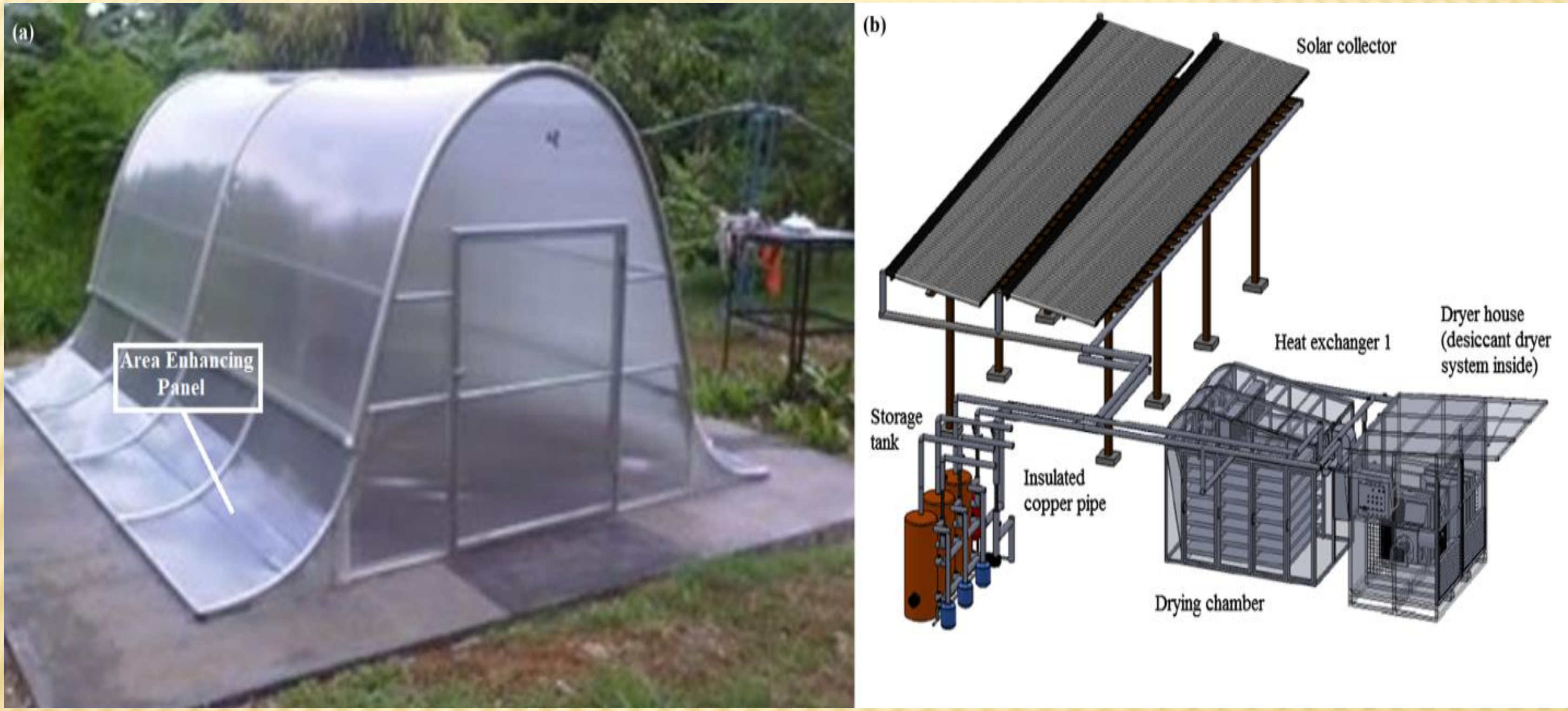
a) Reverse absorber natural convective solar dryer (b) Dryer with PV/T Panel

ADVANCES IN SOLAR DRYER



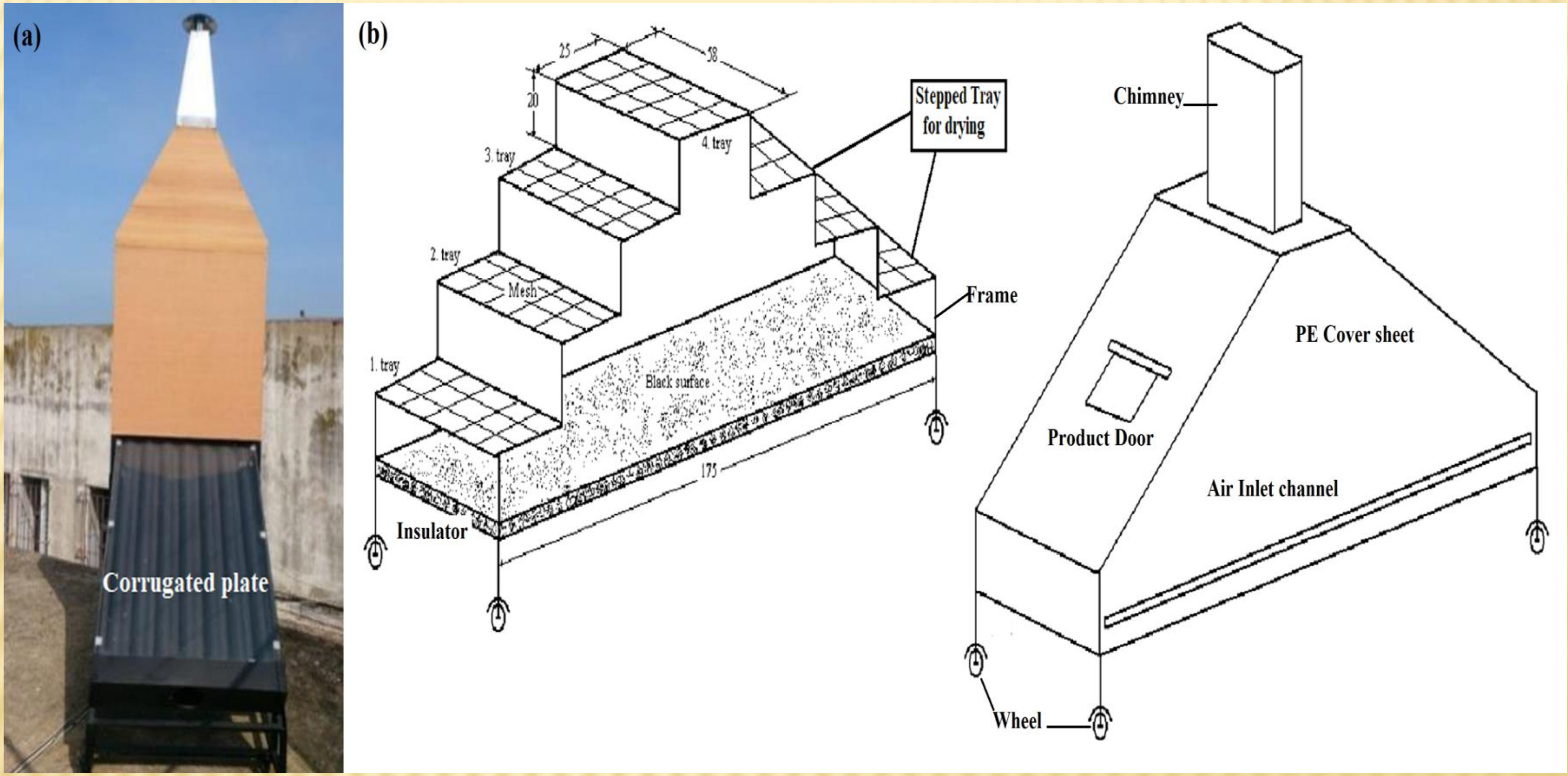
(a) Direct type dryer attached with flat plate collector (b) Dryer with the opaque north wall

ADVANCES IN SOLAR DRYER



(a) Dryer with area enhancing panels (b) Dryer with heat exchanger unit

ADVANCES IN SOLAR DRYER



(a) Dryer with Corrugated collector (b) Dryer with stepped tray

Some of the modifications implemented on the dryers

Method Adopted	Author	Year	Remark
Dryer with PCM / thermal storage materials	Bhardwaj A.K. et al.	2019	Uses Paraffin RT-42 as a PCM and for sensible heat storage, iron scraps with gravels and copper tubes containing engine oil were used.
	Azaizia et al.	2020	the temperature of the air inside the greenhouse dryer with PCM was 5–19°C higher than the ambient condition for 11 hr. The drying time of red pepper in the greenhouse dryer was found lower with PCM (30 hr).
	Dina et al.	2015	Uses absorptive thermal storage material in the indirect dryer with a solar air collector.
PV/T attached dryer	S. Tiwari et al.	2016	Semi-transparent PV module was attached over the glass cover of dryer.
	Saini et al.	2017	
	Fudholi et al.	2016	The dryer was also incorporated with a diesel burner.
Double pass solar air collector heat pump assisted dryer	S. Sevik	2013	Heat pump helps in operating the dryer during night time.
Greenhouse dryer attached with a biomass burner	Aritesty and Wulandani	2014	Wood was used as a bio-fuel.
	Sonthikun S. et al.	2016	Rubber-wood biomass was used as fuel.
Dryer attached with heat exchangers	S. Misha et al.	2016	The heat exchangers were used to exchange heat between the hot water and ambient air supplied to the dryer.
Dryer with reflectors	S. Maiti et al.	2011	Uses two reflectors for concentrating radiations over solar collectors.
	Amer B. et al.	2018	The reflector plate was attached above the solar collector to reflect the solar radiation getting lost to the atmosphere.
Reducing the heat loss from the north wall	Chauhan and Kumar	2017	North wall was made opaque by using nickel polished aluminum sheet over the Thermocol.
	Chauhan et al.	2018	Tested the dryer having an opaque north wall with and without solar collector inside the dryer floor.
			Attached the chapel shaped dryer with the solar collector for

SOME OF THE MODIFICATIONS IMPLEMENTED ON THE DRYERS

- From the researches tabulated in above Table, it can be seen that various efforts have been done to improve dryer performance.
- To make dryer stand-alone, PV/Ts are attached over it while to store the energy for an off sunshine period, thermal energy storage material was used.
- To increase the heat absorption rate of solar collectors attached to dryers, corrugated absorber plates and reflectors were used by the researchers.
- Heat exchangers, auxiliary air heaters, and biomass burners were provided to supply additional heat energy required for drying.
- The efforts had also been put to reduce heat loss through the north wall of greenhouse type dryers in different ways as it is observed that about 30% heat is lost through the north wall of the dryer.

APPLICATIONS OF SOLAR DRYER

- Solar drying is used in various commercial and agricultural applications.
- Different types of crops are dried with the help of solar dryers such as paddy, oilseed, carrot, herb and spices, and vegetables.
- Commercial utilization includes industrial applications of solar drying such as drying of porous materials, bricks, leather, wood and timber, textile, cement, polymers, paper and allied products, tea, dairy products, waste-water treatment, sewage sludge, and pharmaceutical processes.
- In the manufacturing process, approximately 12% of the total energy consumed in the drying system can be saved by using a solar dryer.

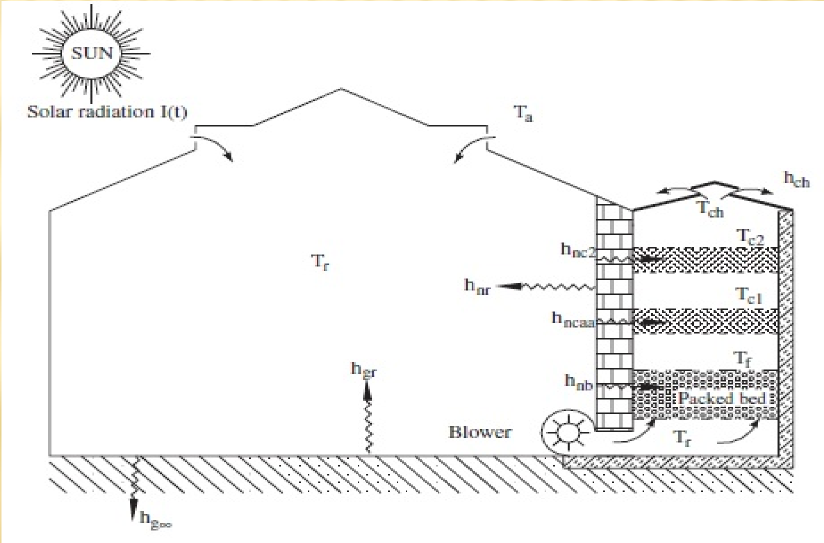
SOME OF THE RESEARCHES ON VARIOUS APPLICATIONS OF SOLAR DRYING IN DIFFERENT SECTORS

Sr. No.	Sector	Author	Year	Purpose
1.	Marine industry	Murali et al.	2021	Shrimps drying
2.	Tea industry	Pou and Tripathy	2020	Black tea drying
		Ozturk and Dincer	2019	Tea leaves drying
3.	Sugarcane industry	Subahana and Natarajan	2016	Sugarcane trash drying
4.	Rubber industry	Sonthikun S. et al.	2016	For drying rubber sheets
5.	Steel wire industry	A.G. Ferreira et al.	2014	For drying industrial waste
6.	Wood and timber industry	Perre P. and Keey R.B.	2014	Wood Drying
7.	Milk powder industry	Kumar M.	2014	Khoa Drying
		Atkins M.J. et al.	2010	Milk Drying
8.	Silk Production	Singh P.L.	2011	Cocoon drying
9.	Waste water treatment	L. Bennamoun	2012	For drying sludge
		N. Kamil Salihoglu et al.	2007	

PREVIOUS STUDIES ON SOLAR DRYERS

Dilip Jain (2005)

- Developed a hybrid solar dryer in which the tray type dryer including thermal storage material at the bottom was attached to the north wall of the greenhouse. The schematic diagram of the greenhouse attached with separate drying chamber is shown in Fig.
- During sunshine hours, the hot air from greenhouse is supplied to the drying chamber through blower while during off sun shine hours the heat stored in the thermal storage material was used for drying.
- The greenhouse had floor area of 24 m^2. Thermal model was developed to study the effect of size and mass flow rate of air on the crop temperature.



The schematic view of greenhouse with separate drying chamber

PREVIOUS STUDIES ON SOLAR DRYERS

Barnwal and Tiwari (2008)

- Developed the PV/T integrated HGSD at Indian Institute of Technology, New Delhi, India. The dryer was even span roof type having 6.5 m^2 floor area and enclosed with polyethylene sheet as shown in Fig.
- DC fan powered by PV modules is used to force air inside the dryer. Matured (GR-II) and pre-matured (GR-I) grapes are dried in open sun and in drier and the observations were compared. The heat transfer coefficient for GR-II type is higher than GR-I type.

PVT integrated HGSD

PREVIOUS STUDIES ON SOLAR DRYERS

Serm Janjai (2012)

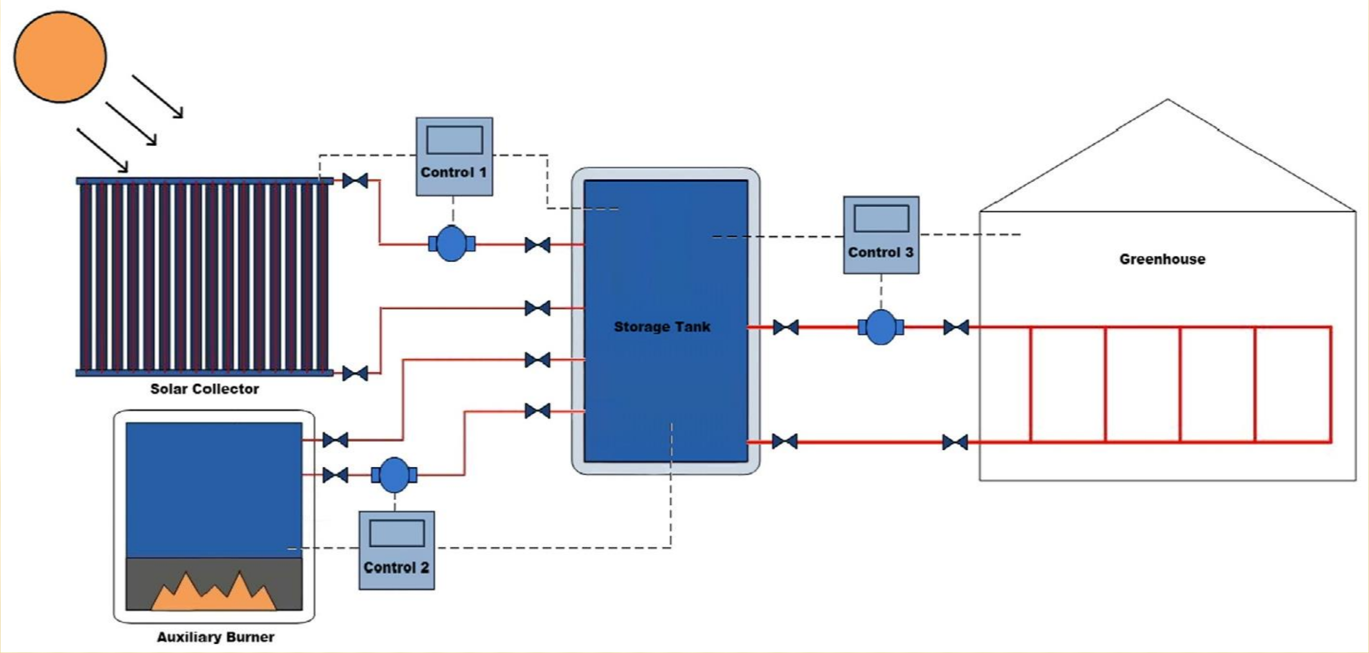
- Constructed the parabolic shaped greenhouse attached with LPG gas burner at Nakhon Pathom, Thailand. The dryer had floor area of 160 m^2 and enclosed with polycarbonate sheet.
- Nine DC fans operated by PV panels were provided to main air circulation. The HGSD integrated with LPG burner is shown in Fig.
- Maximum temperature inside the dryer was 65°C. Result shows that the tomatoes were dried from 54% to 17% (wb) in 4 days. Partial differential equations for the heat and mass transfer taking place inside the dryer were also developed.

Hybrid dryer integrated with LPG burner

PREVIOUS STUDIES ON SOLAR DRYERS

Metin Kıyan, Ekin Bingöl, Mehmet Melikoğlu and Ayhan Albostan (2013)

- Proposed a hybrid setup consisting of greenhouse attached with hot water storage unit and fossil fuel heater. Schematic representation of the proposed setup is shown in the Fig.
- Mathematical model had been developed for the proposed setup. The models are solved by simulation software MATLAB/Simulink. A case study had been done on the greenhouse at Atılım University, Ankara, Turkey to check the feasibility of the developed models.



Schematic diagram of proposed hybrid dryer

PREVIOUS STUDIES ON SOLAR DRYERS

Elsamila Aritesty and Dyah Wulandani (2014)

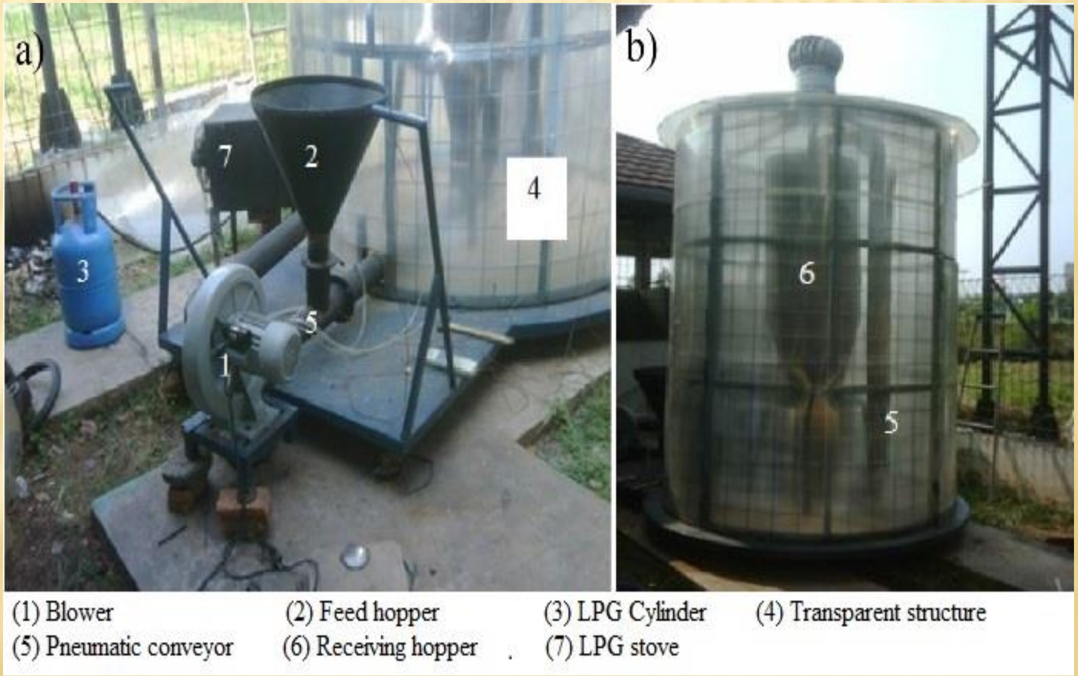
- Developed the rack-type greenhouse solar dryer attached with biomass burner at Faculty of Agricultural Technology, Bogor, Indonesia. The dryer consist of 144 trays and 3 blowers.
- Fig. shows the developed rack-type HGSD. Wild ginger was dried to test the dryer performance. The dryer was tested in no-load and also in two load condition i.e. 21 kg and 60 kg. Result shows that drying time and drying efficiency increases with increase in load.

Rack-type greenhouse attached with biomass burner

PREVIOUS STUDIES ON SOLAR DRYERS

Yefri Chan, Nining Dyah and Kamaruddin Abdullah (2015)

- Developed an integrated collector drying chamber (ICDC) type solar dryer integrated with LPG burner. The developed HGSD with different component attached is shown in Fig.
- Dryer performance was tested with two different loads i.e. 104 kg and 200 kg rough rice. Result shows that the drying time and drying efficiency increases with increase in load.

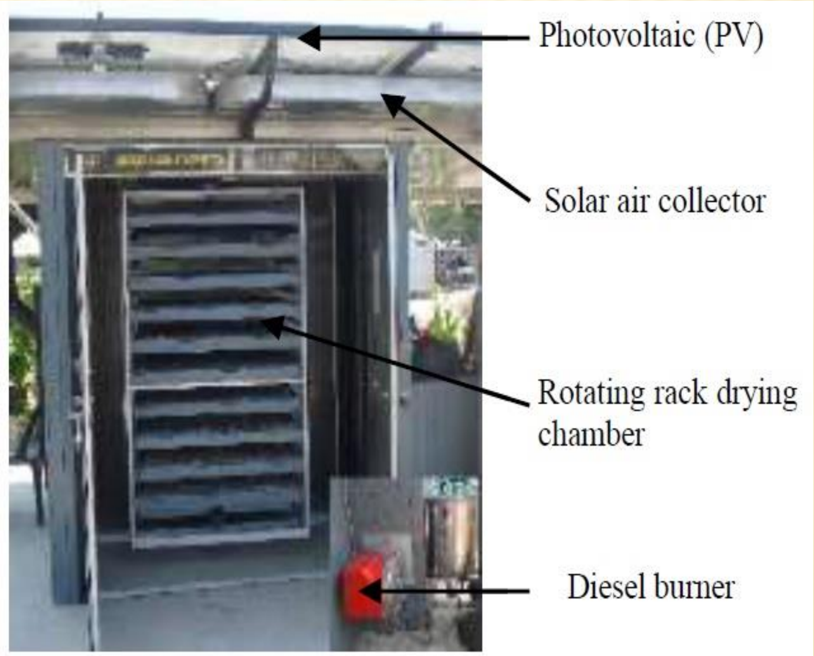


HGSD attached with blower and LPG burner

PREVIOUS STUDIES ON SOLAR DRYERS

Ahmad Fudholi et al. (2016)

- Developed the hybrid dryer incorporating solar collector, PV panels and diesel burner. The developed dryer is located at Johor, Malaysia.
- Fig. shows the developed hybrid dryer. Silver Jewfish was dried inside the dryer in order to determine the energy and exergy of the dryer. Result shows that fish was dried from 64% to 10% (wb) in 8 hours. Also the exergy efficiency lies in the range of 17-44%.

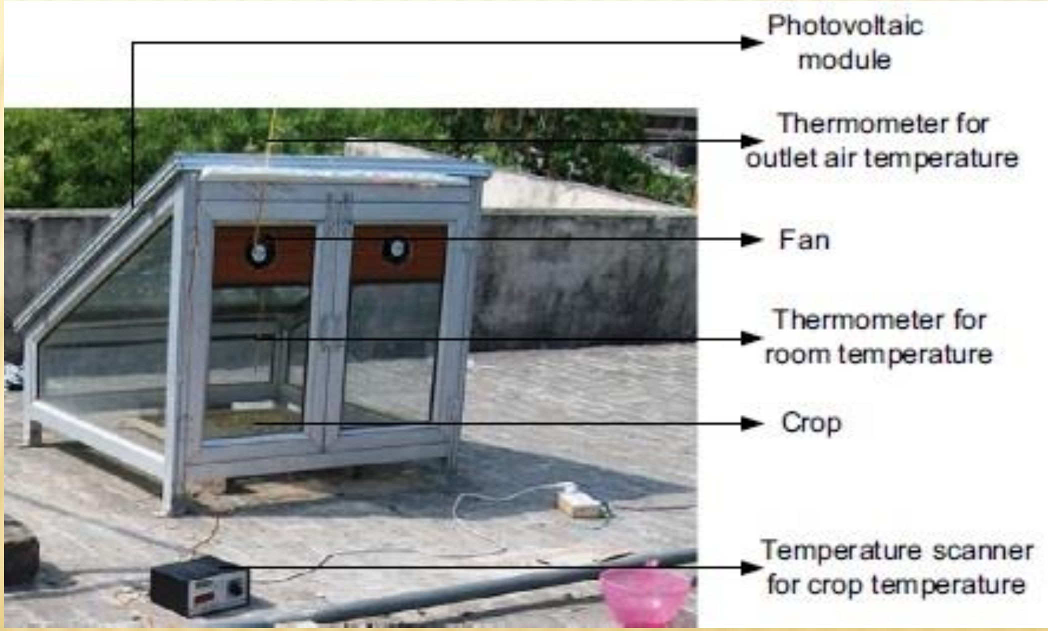


Hybrid greenhouse attached with diesel burner

PREVIOUS STUDIES ON SOLAR DRYERS

Sumit Tiwari, G.N. Tiwari, I.M. Al-Helal (2016)

- Developed the PV/T integrated mixed mode hybrid dryer at Indian Institute of Technology, New Delhi, India. The developed HGSD is shown in Fig.
- The dryer had a floor area of 1.066 m^2 and enclosed with 3 mm glass. Two DC fans operated by PV panels were provided for forced circulation of air. MATLAB 2013a was used for numerical computation of thermal models developed considering parameters like temperature of crop, greenhouse, PV module etc.

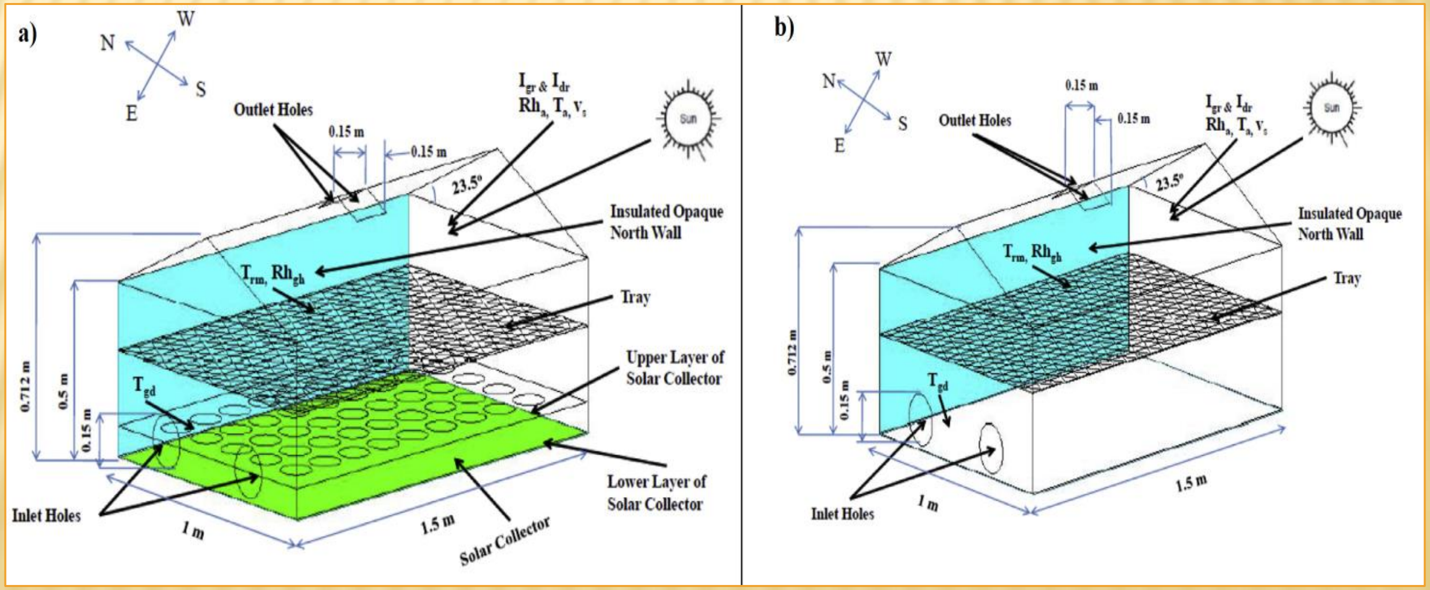


The pictorial view of developed HGSD

PREVIOUS STUDIES ON SOLAR DRYERS

Prashant Singh Chauhan and Anil Kumar (2016)

- Constructed the north wall insulated greenhouse at Energy Centre, Maulana Azad National Institute of Technology, Bhopal, India. The greenhouse was tested with and without solar collector at the ground of the dryer.
- Fig. shows the schematic diagram of the dryer with and without collector. The dryer was operated in passive mode and tested in no-load condition. The dryer performance in terms of heat utilization factor, coefficient of performance (COP), heat loss factor (HUF) etc. were calculated.
- The result shows that the dryer with solar collector has better HUF and COP.



Schematic representation of HGSD (a) with collector and (b) without collector

RECENT STUDIES ON SOLAR DRYERS

Zaineb Azaizia et al. (2017)

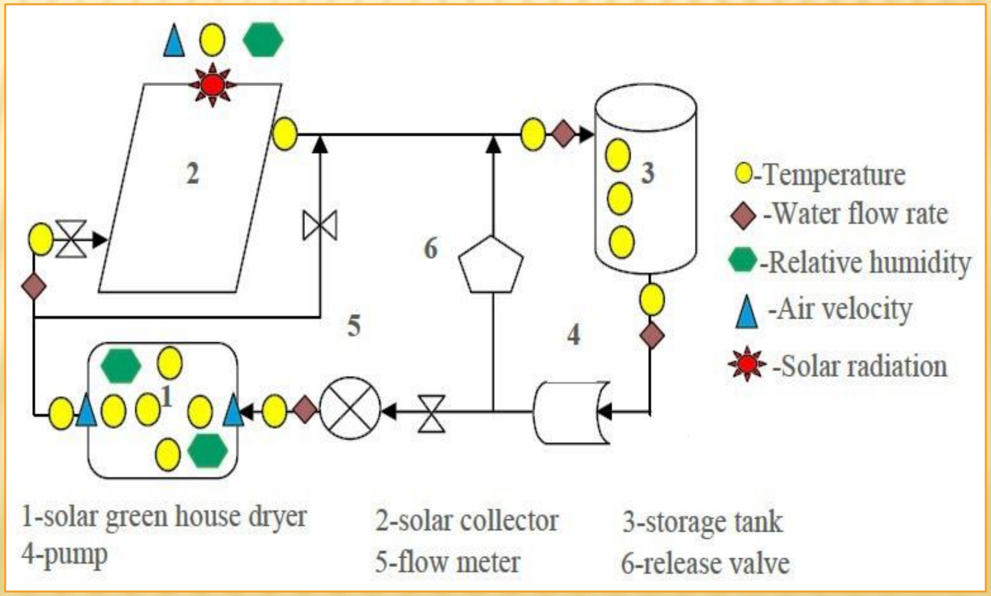
- Developed the hybrid greenhouse at Research and Technology Centre of Energy in North of Tunisia. The dryer had floor area of 14.8 m^2 and central height of 3 m. The plexiglass enclosed dryer was attached with solar collector having area 2 m^2.
- Fig. shows the developed HGSD with flat plate collector. TRNSYS program was used to develop the mathematical model for the proposed system. The effect of air flow rate, collector and drying area on the humidity and temperature inside the greenhouse was studied. Result shows that the optimum collector area was 2 m^2 with optimum air flow rate of 250 kg/h and optimum drying area of 40 m^2.

Greenhouse dryer attached with flat plate collector

RECENT STUDIES ON SOLAR DRYERS

S. Deeto, S. Thepa, V. Monyakul and R. Songprakorp (2017)

- Developed a greenhouse attached with solar collector and heat storage unit at King Mongkut's University of Technology, Bangkok, Thailand. The floor area of the dryer was 0.3 m^2 and mounted on a black PVC sheet. The block diagram of the proposed hybrid setup is shown in Fig.
- A water storage tank of 180 liter capacity and insulated with polyurethane foam was attached to the dryer for storing hot water. The result shows that the coffee beans were dehumidified from 55% to 12% (wb) in 12 hours. Also investigate the model suitable for coffee drying.

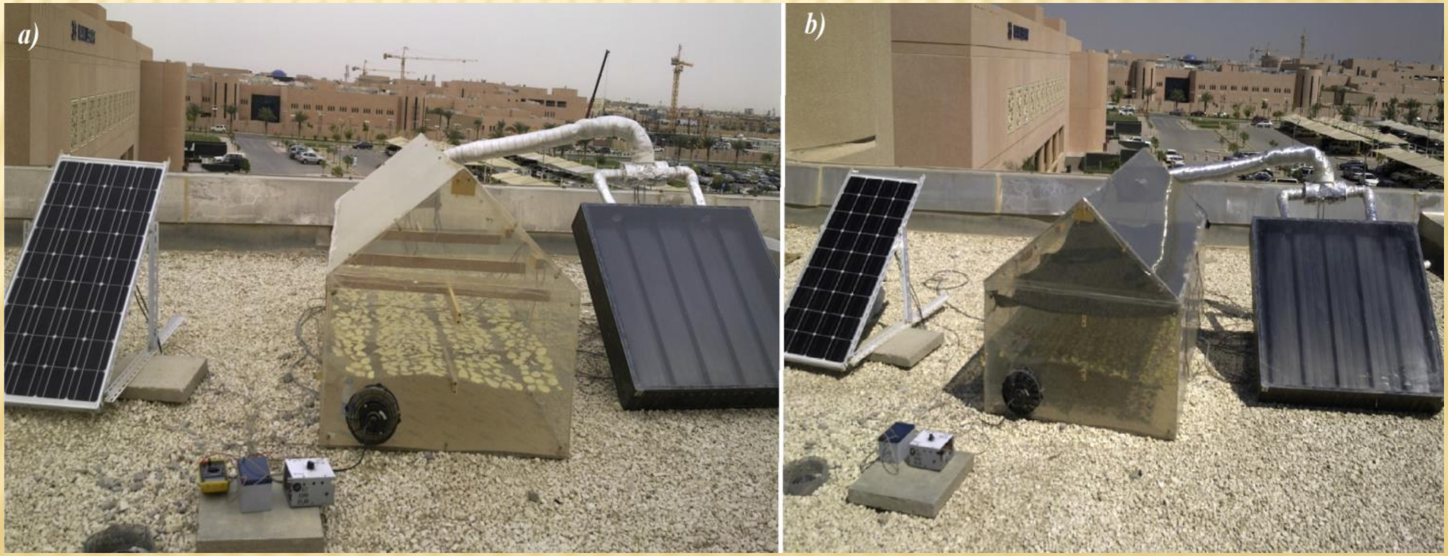


Block diagram of proposed hybrid setup

RECENT STUDIES ON SOLAR DRYERS

Mohamed A. Eltawil, Mostafa M. Azam and Abdulrahman O. Alghannam (2018)

- Developed the tunnel type dryer attached with flat-plate collector and PV panels at King Faisal University, Saudi Arabia. The tunnel was even span roof type having floor area of 2 m^2 and enclosed with plexiglass of thickness 2mm.
- Fig. shows the developed solar tunnel hybrid dryer. The dryer was tested with and without load and also with and without thermal curtain. The potato was dried inside the dryer with air flowing at different speeds. The drying efficiency reaches to maximum value of 34.29% at air flow rate of 0.0786 kg/s with thermal curtain above the potato slices.

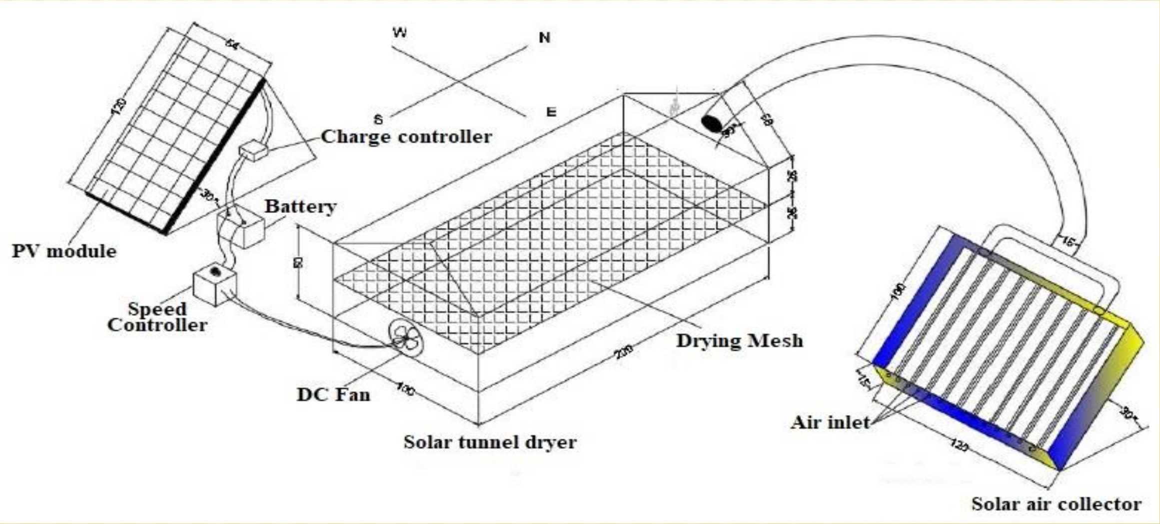


Greenhouse attached with flat-plate collector and PV panel (a) without thermal curtain and (b) with thermal curtain

RECENT STUDIES ON SOLAR DRYERS

Mohamed A. Eltawil, Mostafa M. Azam and Abdulrahman O. Alghannam (2018)

- Developed the tunnel type dryer attached with flat-plate collector and PV panels at King Faisal University, *Saudi Arabia*. Schematic diagram of developed hybrid dryer is shown in Fig.
- The peppermint is dried inside the dryer in one, two and three layers for evaluating dryer performance. The maximum drying time was 360 min inside dryer while 420 min in open sun. Use of thermal curtain gives better quality mint as compared to natural sun drying. The dryer had an efficiency of 30.71% and energy payback period of 2.06 years.



Schematic diagram of greenhouse attached with solar collector and PV module

RECENT STUDIES ON SOLAR DRYERS

Pranav Mehta et al. (2018)

- Constructed a hemi-cylindrical shaped greenhouse dryer attached with flat-plate collector at CSIR-Central Salt & Marine Chemicals Research Institute, Gujarat, India. The photograph of the developed HGSD is shown in Fig.
- Fish was dried inside the dryer to test its performance. In order to predict the collector outlet temperature, mathematical model was developed and them solved by SageMath programming language.
- Drying time of fish was 18 hours inside the dryer while it takes 38 hours in open sun.

Rack-type HGSD attached with flat-plate collector

RECENT STUDIES ON SOLAR DRYERS

Hamdani, T.A. Rizal, Zulfri Muhammad (2018)

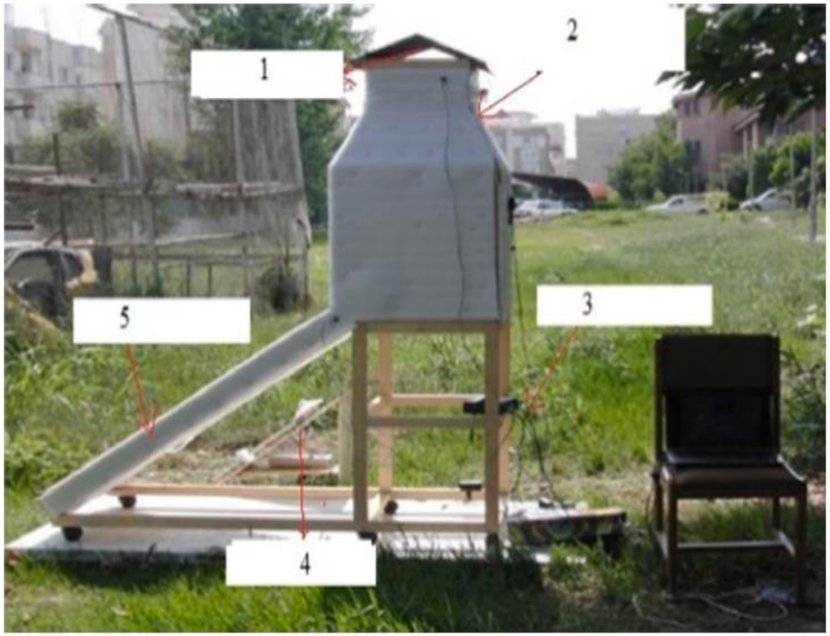
- Manufactured the tunnel type greenhouse dryer attached with biomass burner at Samudra University, Aceh, Indonesia. The fabricated picture of the developed hybrid dryer is shown in Fig.
- Drying area was 2.08 m^2 and dryer was covered with transparent plastic sheet. The Queenfish was dried for evaluating the dryer performance. Wood was used as fuel for supplying hot air during off-sunshine hours. Result shows that in 15 hours only the fish was dried to 12% moisture level. Also economic analysis of the dryer was also carried out.

The fabricated HGSD attached with biomass burner

RECENT STUDIES ON SOLAR DRYERS

S. Shamekhi-Amiri et al. (2018)

- The effect of airflow rate on the performance of the dryer was studied for drying lemon balm leaves. By increasing the flow rate from 0.006125 m^3/s to 0.01734 m^3/s, the collector thermal efficiency increased by about 20%, and the further increase in the flow rate decreased the collector efficiency.
- Moisture content reduced by 87.5% and Thermal efficiency improved by 20% with the increase in mass flow rate of air.



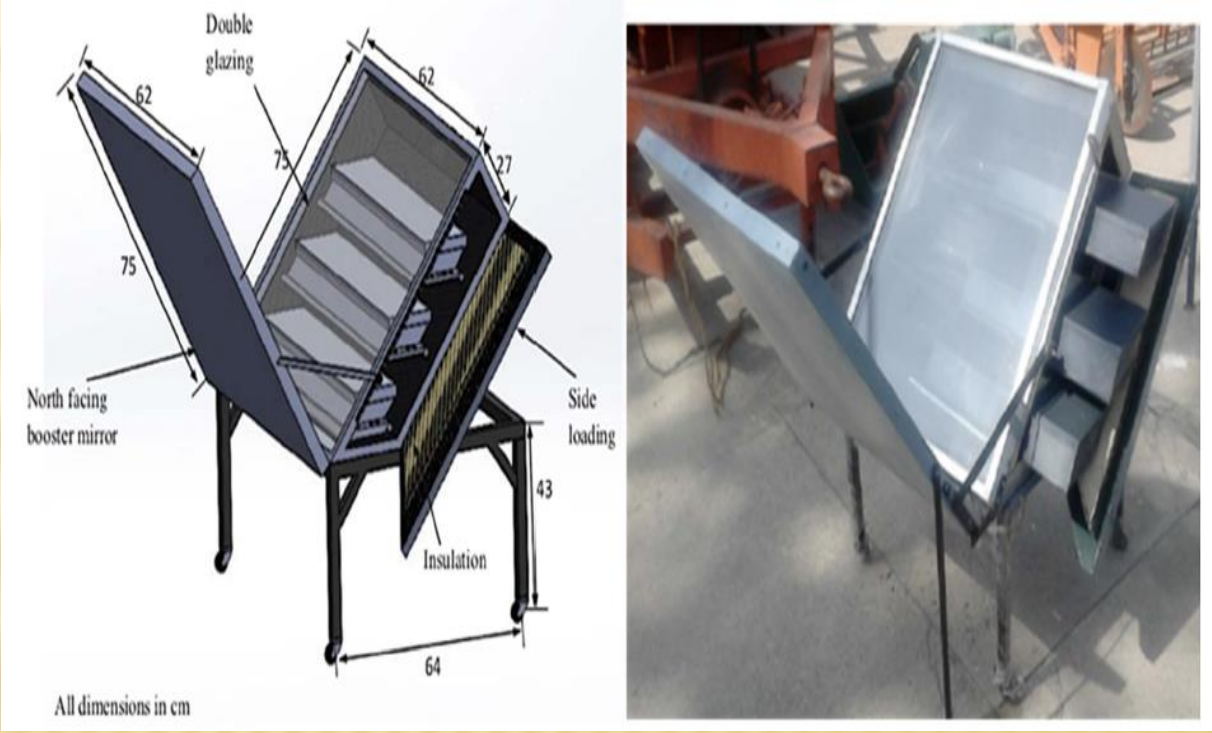
1. Hot air outlet 2. Dryer cabinet 3. Thermocouples 4. Pyranometer 5. Solar air heater

Indirect double pass packed bed forced convection solar dryer

RECENT STUDIES ON SOLAR DRYERS

Singh and Sethi (2018)

- Carried experiment on direct box type solar dryer using flat plate collector.
- A multi-shelf inclined solar cooker cum-dryer was developed by using galvanized iron (GI) sheet and double-glazing glass as the transparent cover.
- Environmental impact analysis showed a significant saving in biomass fuel consumption and reduction of CO_2 emission.

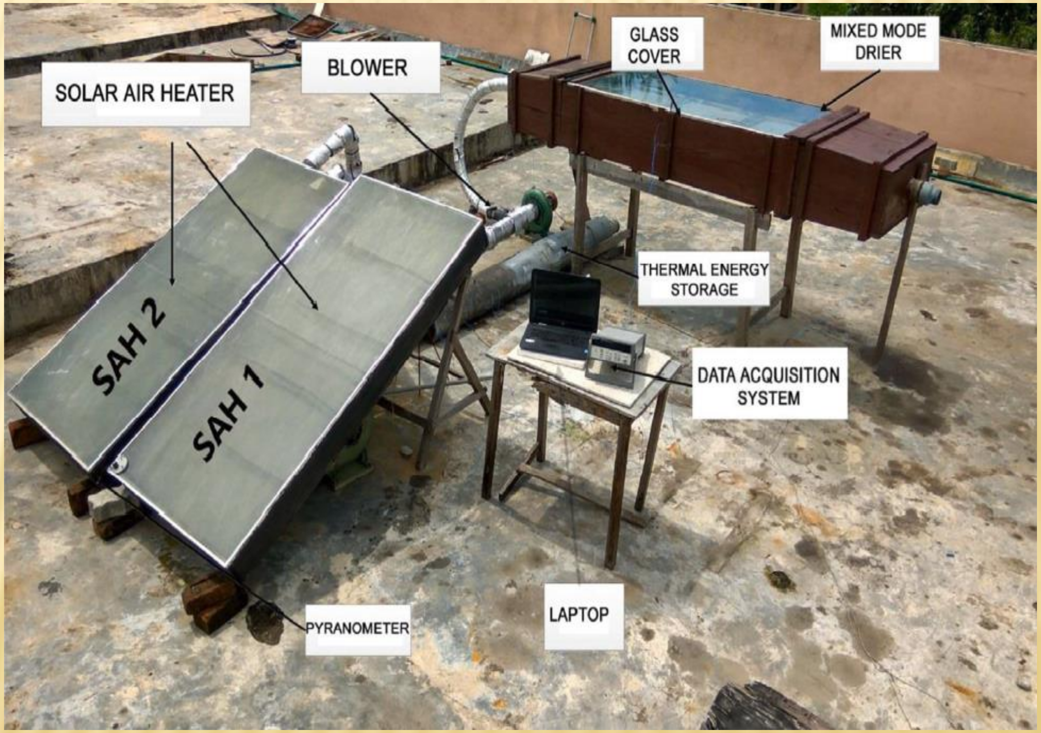


Box shape drying chamber of multi-shelf inclined solar cooker-cum-dryer

RECENT STUDIES ON SOLAR DRYERS

Lakshmi et al. (2019)

- Carried out an experimental investigation to evaluate the performance of a mixed-mode forced convection solar dryer when it was used for drying stevia leaves. 5.5 hours taken for reducing the moisture content to be about 5.3%.
- Overall dryer efficiency was 33.5% and average exergy efficiency was 59.1%.
- The Payback period was 0.65 years.

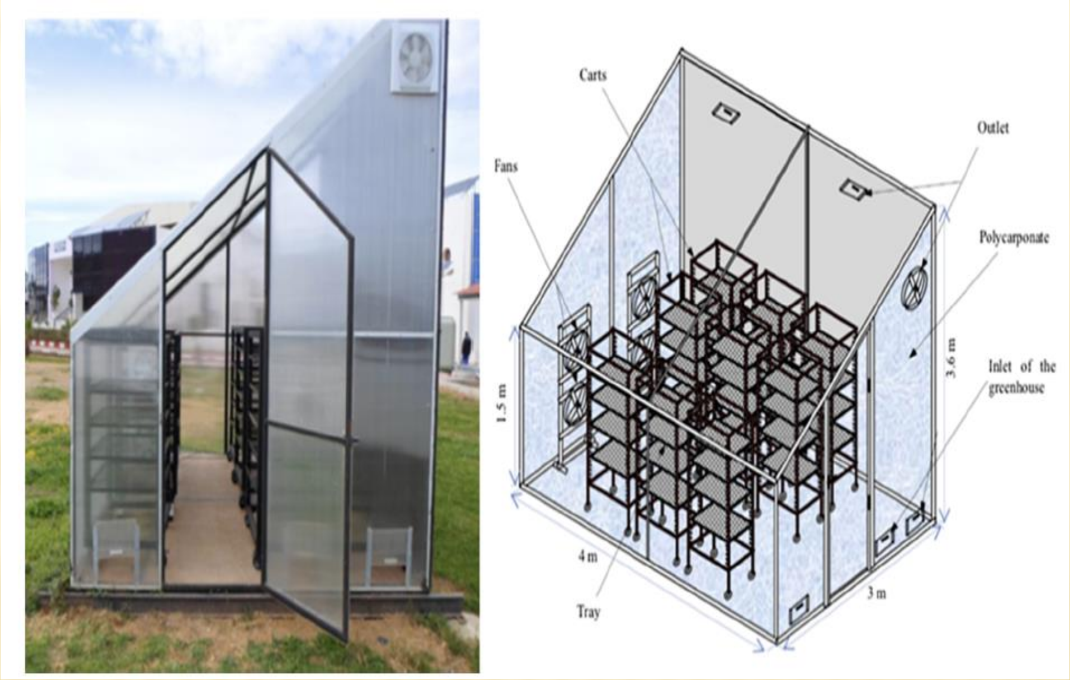


Continuous flow mixed-mode forced convection solar dryer

RECENT STUDIES ON SOLAR DRYERS

Badaoui et al. (2019)

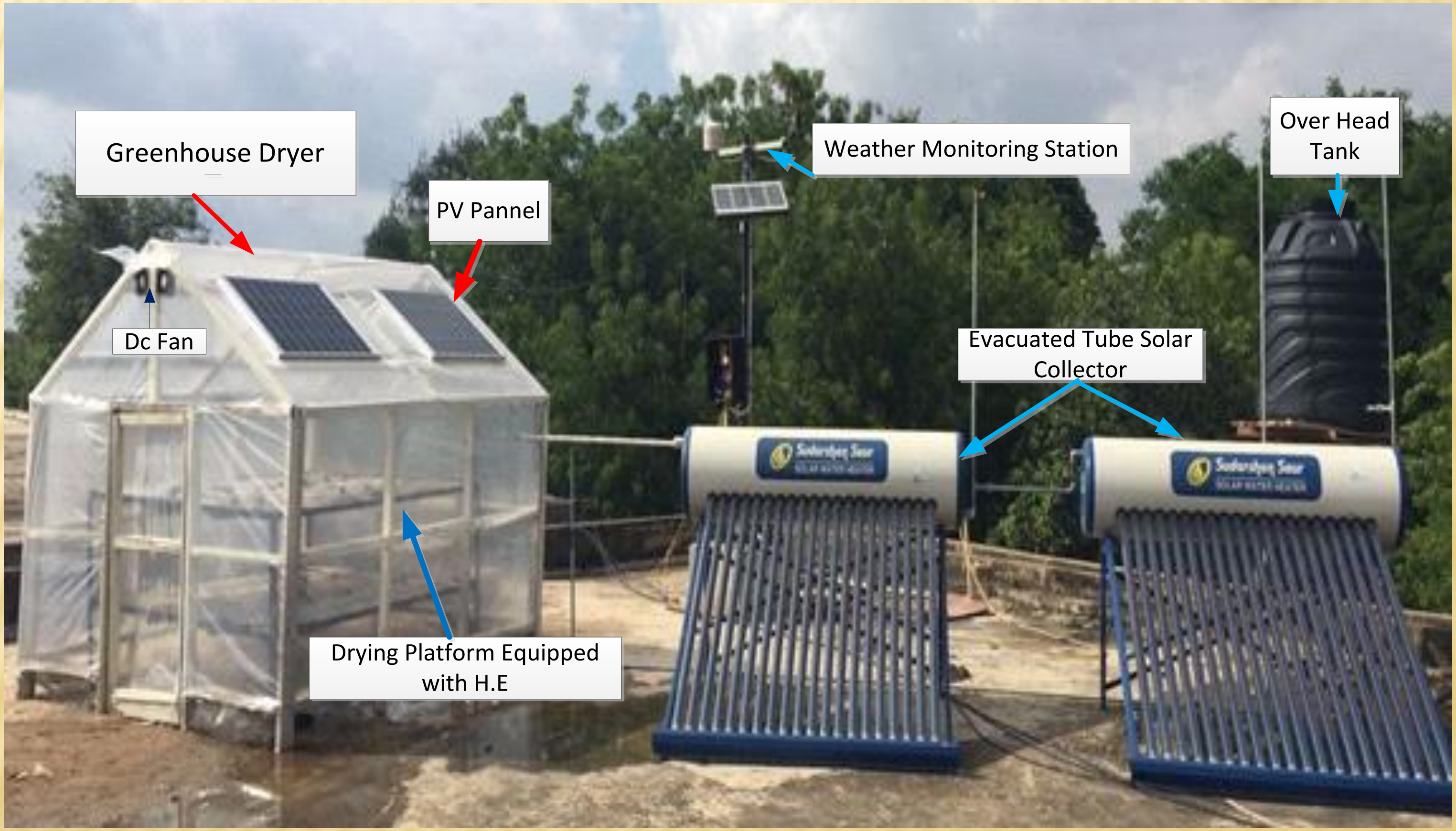
- Carried experimental study on tomato pomace waste drying. Fig. is shown below.
- Roof and three sides of the drying chamber walls were made from polycarbonate sheets of 70% transmittance value and the rear wall was insulated with a black colour polystyrene.
- It is able to dry the tomato pomace waste at temperature range of 40 to 58°C within 5 hour period.



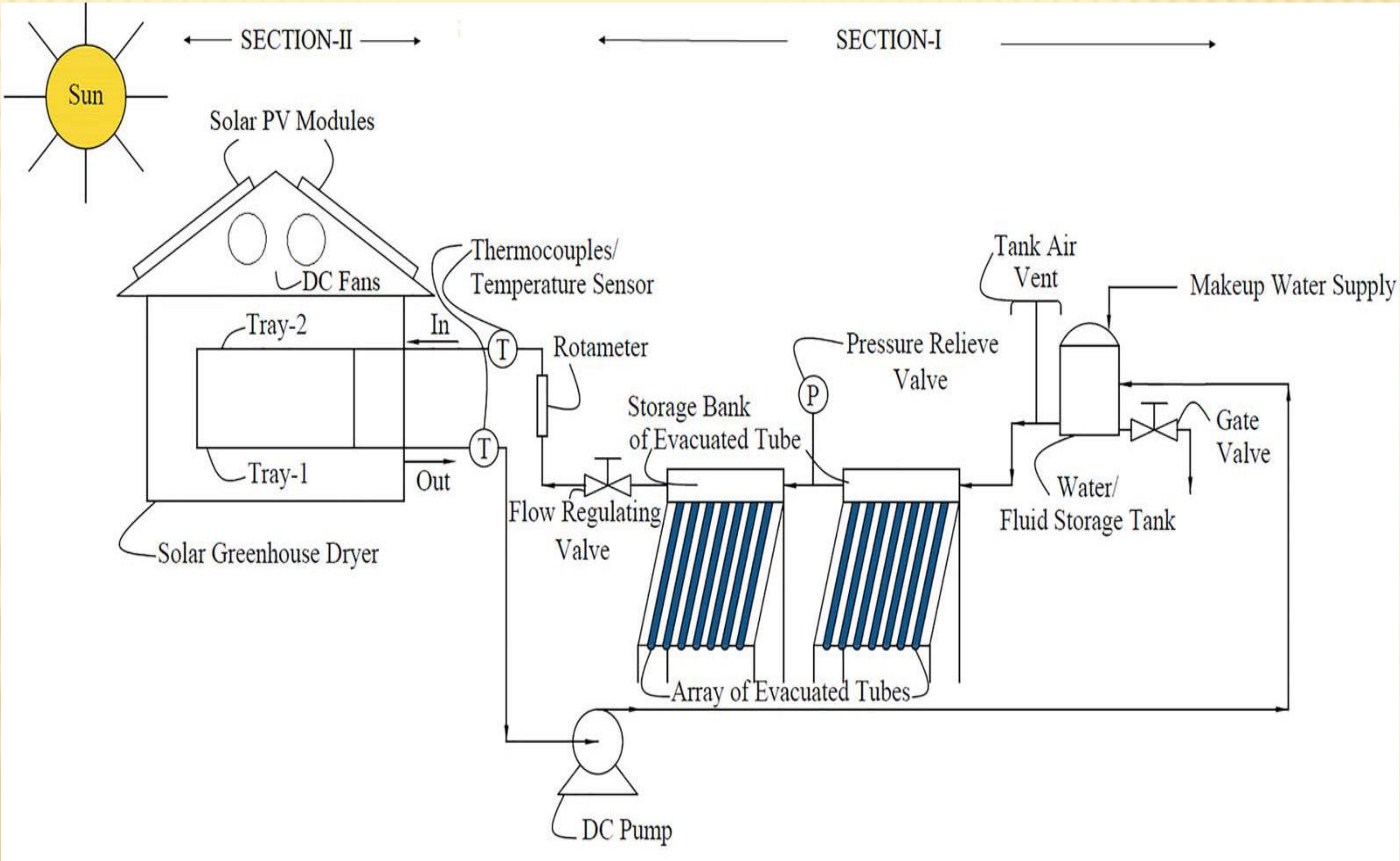
Greenhouse solar dryer

RECENT STUDIES ON SOLAR DRYERS: ANIL KUMAR LAB

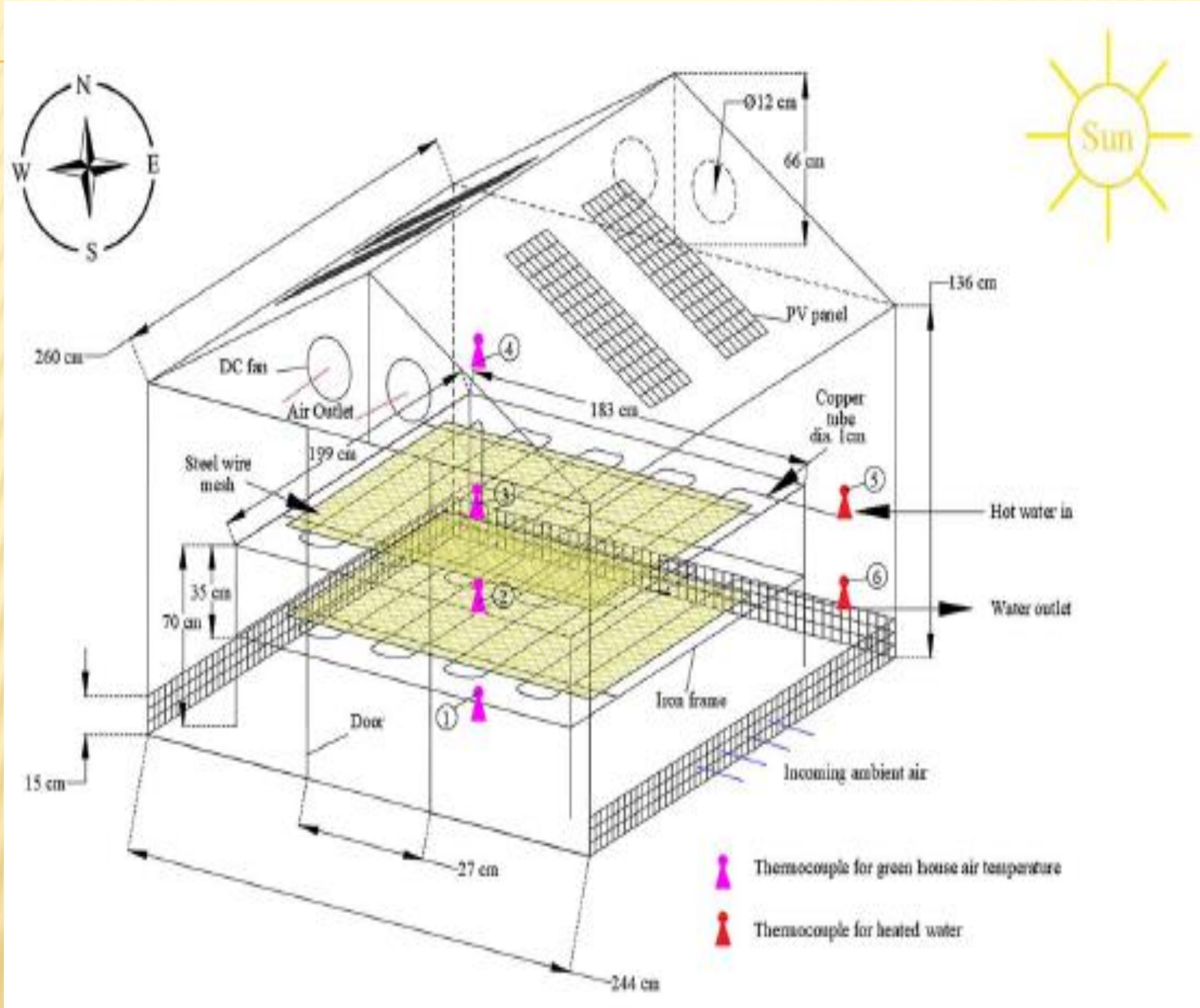
Exchanger-Evacuated Tube Assisted Drying System



Schematic of Exchanger-Evacuated Tube Assisted Drying System



Inside Layout of Exchanger-Evacuated Tube Assisted Drying System



Thermal Performance of HE-ETADS

Moisture Content

MC is amount of water available in the sample at an instant and can be calculated in percentage of MC. MC on wet basis (%wb) can be determined by following Eq.20 (Prakash and Kumar 2017):

$$MC = \frac{m_i - m_f}{m_i} \times 100$$

Drying Rate (DR)

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t}$$

Moisture Ratio

$$MR = \frac{M_t - M_e}{M_i - M_e}$$

Equilibrium Moisture Content

$$RH = exp\left(\frac{-11.08492}{RT_{abs}} \times M_e^{-0.886330}\right)$$

Solar collector efficiency (η_C)

Ratio of heat energy absorbed by water to received solar energy on the collector as

$$\eta_C = \frac{M_{water} \times C_p (T_{co} - T_a)}{A_c \times I_G}$$

Thermal efficiency of solar drying system

$$\eta_D = \frac{(m_i - m_f) \times L_w + C_{pw}(T_o - T_a)}{Q_s} \times 100\%$$

Exergy efficiency of Developed Solar Dryer

Exergy inflow of the drying cabin:

$$Ex_i = m_a C_{pa} \left[(T_i - T_a) - T_a \ln \frac{T_i}{T_a} \right]$$

Exergy outflow of the drying cabin:

$$Ex_o = m_a C_{pa} \left[(T_o - T_a) - T_a \ln \frac{T_o}{T_a} \right]$$

Exergy losses:

$$Ex_{ls} = Ex_i - Ex_o$$

Exergy Efficiency:

$$\eta_{EE} = \frac{Ex_o}{Ex_i}$$

Basic Quality Parameters of Dried Product

Color indices of dried garlic:

Color of dried product is measured at surface through a colorimeter (Color Flex, Hunter Lab) with D-65 illuminant. Total color difference/change can be expressed as:

$$\Delta E = \sqrt{(\Delta L_o)^2 + (\Delta a_o)^2 + (\Delta b_o)^2}$$

Hardness of dried product:

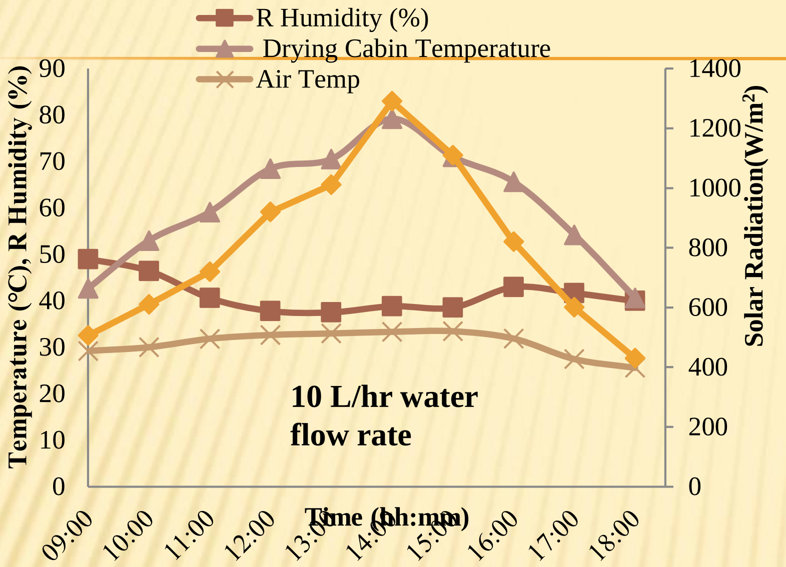
Hardness is the highest power applied to the dried piece throughout the measuring process. CT3 texture analyzer was used to observe the hardness of the dry product after rehydration. To conclude the final outcomes of it, at least an average of 12 observations is required.

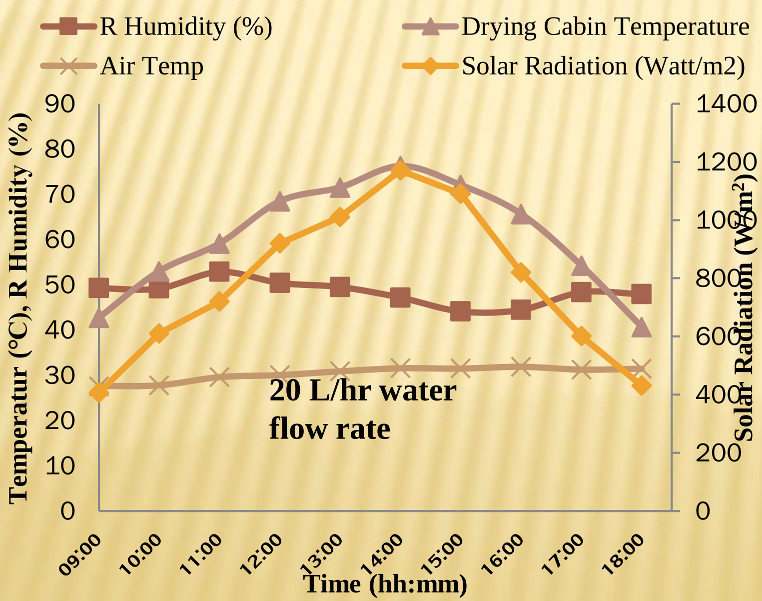
Contraction/Shrinkage factor:

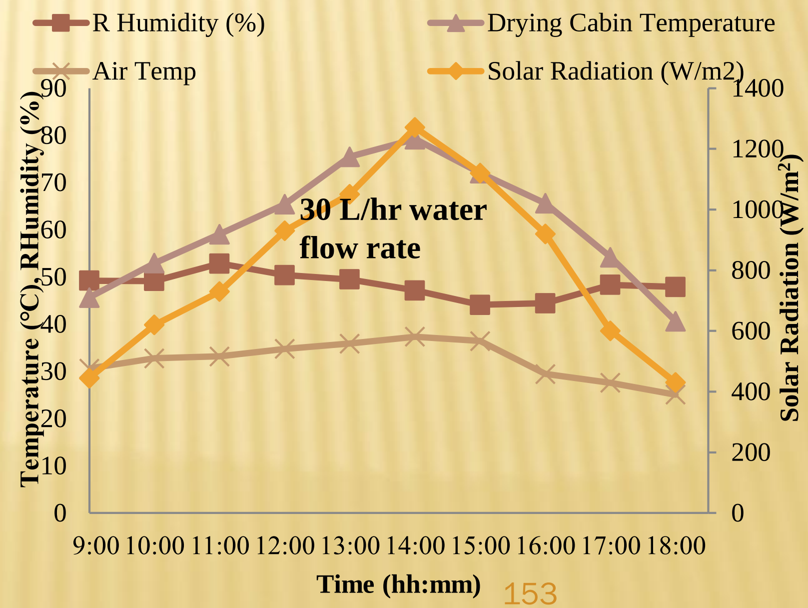
Variation in the size of dried product as associated with the fresh product's actual size is termed as contraction factor in %

$$\text{Contarction Factor} = \frac{(V_{actual} - V_{final})}{V_{final}}$$

Drying Parameter inside HE-ETADS without load condition at different water flow rate







PUBLISHED WORK ON SOLAR DRYER IN 2020

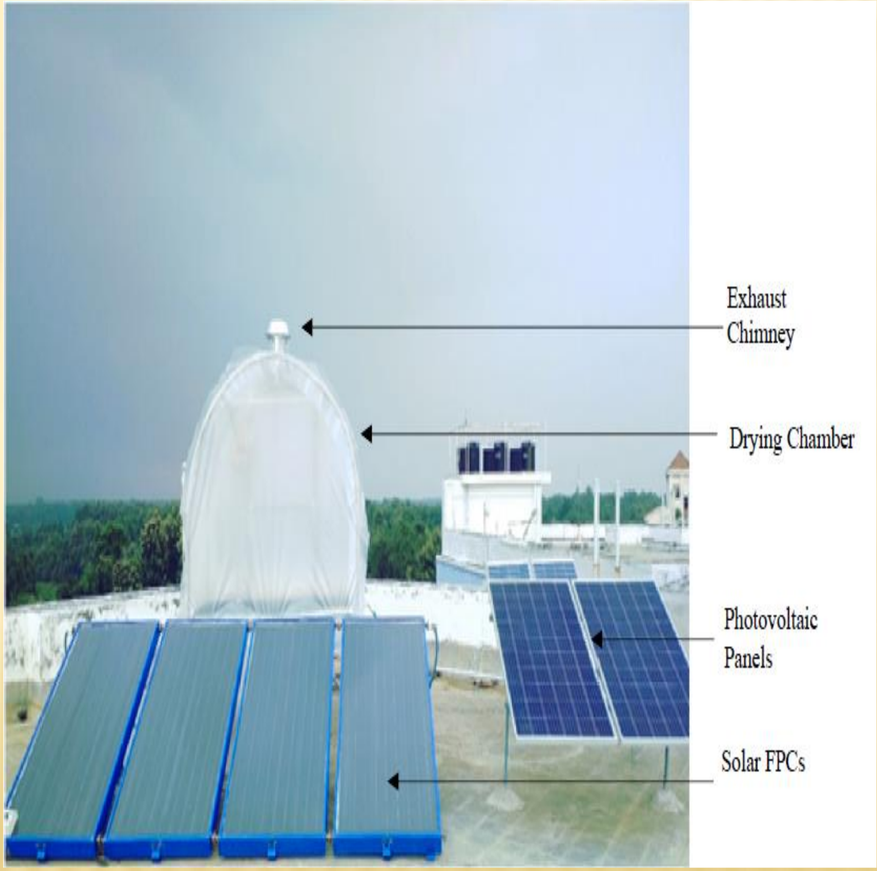
Mohammed S. et al. (2020)

- A modified passive-mode hybrid solar dryer called as an Improved Solar Dryer (ISD) and PV-assisted hot air dryer using active-mode hybrid solar dryer called as Solar Photovoltaic and Electric (SPE) were developed for drying fruits in Uganda.
- The drying performance results show that the mean drying air temperatures achieved by the ISD and SPE dryers were 31.9 and 41.1 °C respectively; relative to the 27.6 °C for the open sun drying. It took the ISD and SPE dryers 10 and 18 h to effectively dry the pineapple, respectively as opposed to the 30 h taken by the open sun drying.
- The results confirm the superior performance of the ISD and SPE dryers than the OSD method.

PUBLISHED WORK ON SOLAR DRYER IN 2020

Andharia J.K. et al. (2020)

- In this study, a 6 kg/batch mixed-mode solar thermal dryer was developed and installed at Agartala.
- Moisture content of the natural rubber sheets dried in the solar thermal dryer was reduced from 40% to 4% vis-à-vis 11% in open sun drying condition in 3 days' time on wet basis.
- Quality of the solar dryer dried sheets was found to be superior to the open sun dried ones.
- Innovative features of the developed solar thermal dryer include (a) recirculation of spent dehumidified air to minimize thermal energy loss (b) 90% UV cutoff in the drying chamber leading to better color retention of the product (c) solar photovoltaic operated dehumidifier for use during night to prevent reabsorption of moisture.



PUBLISHED WORK ON SOLAR DRYER IN 2020

Spall and Sethi (2020)

- An innovative design of front loaded multi-rack tray solar cabinet dryer was developed having optimally inclined reflective north wall which utilizes reflected component of the solar radiation in addition to the beam radiation for efficient drying particularly in winter when conventional dryer does not perform well at higher latitudes (>30°N).
- Use of reflective north wall enhances the radiation capture by 37.58%, 31.57% and 23.24% at 30°, 40° and 50°N latitude respectively in winter.
- Total reduction in drying time for carrot drying was observed to be 20% and 15% under natural and forced convection modes respectively.

PUBLISHED WORK ON SOLAR DRYER IN 2020

Ndukwu M.C. et al. (2020)

- The paper presents an active mix-mode wind-powered fan solar dryer (AWPFS) with a passive mix-mode non-wind-powered solar dryer (PNWPS) evaluated with pre-treated potato slices.
- The two dryers were tested with and without glycerol as thermal energy storage. The results indicate that drying with AWPFS integrated with glycerol showed shorter drying time than drying with AWPFS only or PNWPS.
- Dipping the potato in a salt solution and blanching for 30 s before drying quickened the drying rate of the potato compared to other treatments.
- The drying efficiencies ranged from 25.031% to 31.5%, while the exergy efficiency ranged from 14.5 to 80.9%.

PUBLISHED WORK ON SOLAR DRYER IN 2020

Dutta P. et al (2020)

- The work focuses on drying of Garcinia pedunculata in an efficiently developed free convection corrugated solar dryer (FCCSD) and conventional open sun.
- Experimental solar drying results for two batches are presented. The moisture contents of Garcinia pedunculata in the dryer was reduced to 7.22% (wb) for the first batch and 7.1% (wb) for the second batch in 28 h from the initial of 88% (wb) of moisture content.
- Moisture content was reduced to 10.18% (wb) and 10.08% (wb) for the first and second batches respectively in 55 h in open sun drying.

PUBLISHED WORK ON SOLAR DRYER IN 2020

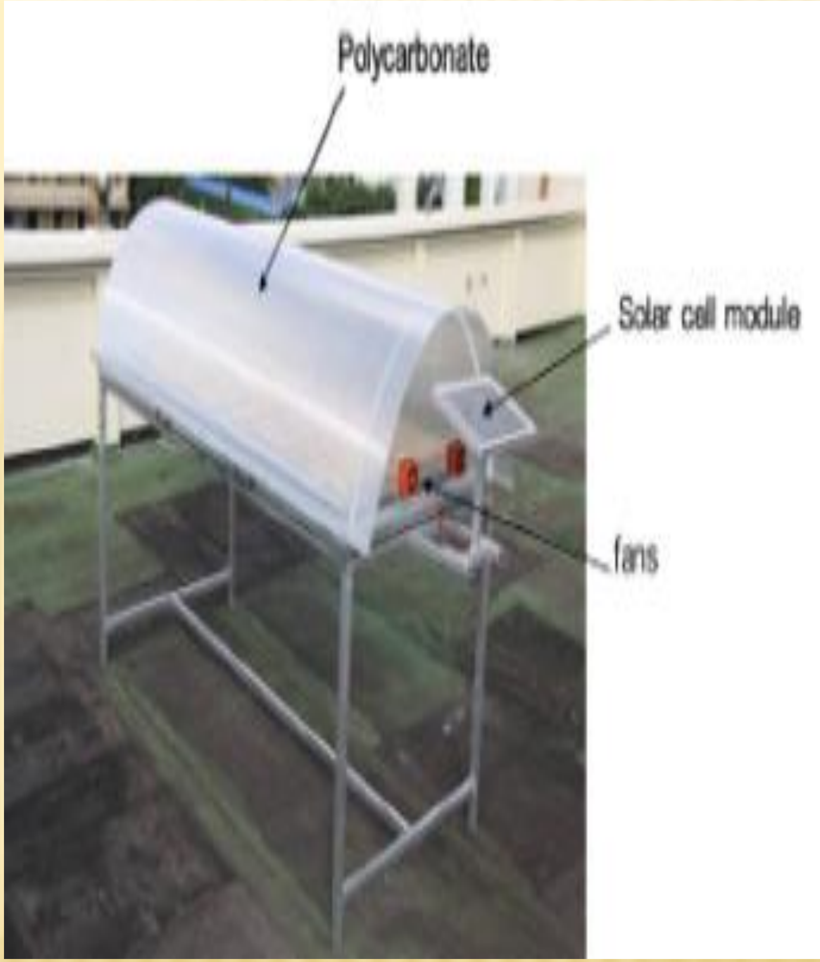
Sethi and Dhiman (2020)

- A solar-cum-biomass hybrid greenhouse crop dryer (HGCD) is developed to work on solar energy and on biomass heat for 24 h continuous operation at constant drying temperature of 62°C.
- Vertical gap (clearance) between two consecutive trays is optimized for selected latitudes of 30°, 35°, 40°, 45° and 50°N.
- Global solar radiation and thermal models are developed to predict the solar radiation availability and HGCD chamber air temperature (T_{hgcd}). Forced draft paddy straw bale combustor (FDPSBC) is used to generate flue gas above 500°C temperature as supplemental heat source and coupled with flue gas heat transfer pipe network laid inside the HGCD to maintain T_{hgcd} at constant temperature.

PUBLISHED WORK ON SOLAR DRYER IN 2020

Nabnean and Nimnuan (2020)

- In this study, the performance of direct forced convection household solar dryer for drying **banana** is presented.
- A solar dryer with a polycarbonate cover on a flat plate collector was constructed and it was designed in the parabolic shape.
- A polycarbonate cover is used to reduce heat losses while allowing the incident solar radiation to transmit into the dryer. Five batches of banana were dried in this solar dryer during January–July 2019.
- For each batch, 10 kg of bananas were dried. The moisture content of the banana in the dryer was reduced from an initial value 72% (wet basis, wb) to a final value of 28% (wb) within 4 days, whereas the moisture content of the sun dried samples was reduced to 40% (wb) in the same period.



PUBLISHED WORK ON SOLAR DRYER IN 2020

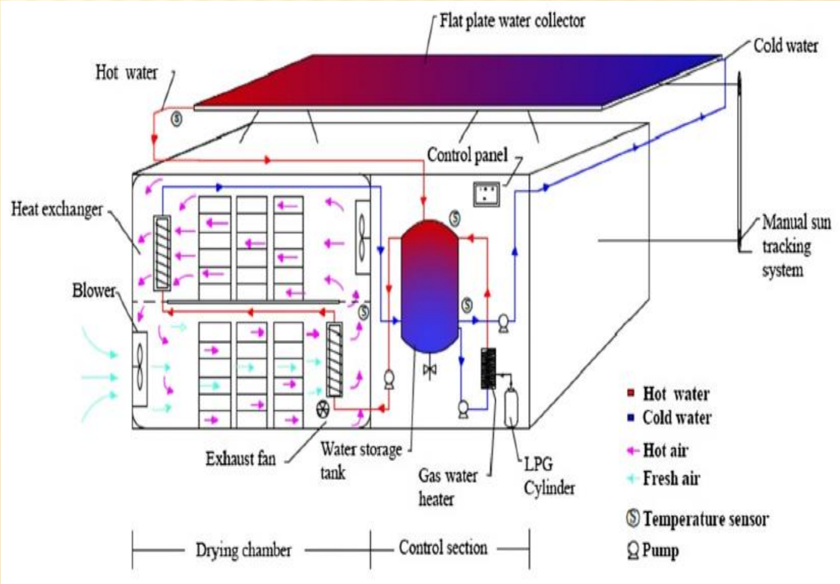
Jagadeesh D. et al. (2020)

- In this study, selecting an ideal shape of greenhouse dryer among the other shapes is investigated.
- Six shapes of solar greenhouse dryers are designed in such a way that each dryer maintains the same volume of 30 ft^3.
- Six shapes are Parabola, Quonset, Modified Quonset, Pyramid, Igloo and tropical. The inside temperature of greenhouse dryer is in the following order from maximum to minimum, Quonset, Tropical, Pyramid, Parabola, Modified Quonset and igloo during summer season.
- The ideal shape of the solar greenhouse dryer is Quonset Shape; it generates a maximum of 72 °C in summer and 66 °C in winter.

PUBLISHED WORK ON SOLAR DRYER IN 2020

Murali et al. (2020)

- Solar dryer with a TES system was developed for shrimps drying.
- The water-based TES system stored the energy during peak sunshine hours. Also, the dryer was assisted with liquefied petroleum gas (LPG) as an auxiliary heating source.
- 50 kg shrimp were dried from 76.71% (wb) to 15.38% (wb) within 6 hr of drying, with 73.93% of heat from solar collector and 26.07% of the energy from LPG water heater system.
- Drying efficiency of the system was observed to be 37.09%.



PUBLISHED WORK ON SOLAR DRYER IN 2021

Singh et al. (2021)

- Carried experimental work on Fenugreek leaves using indirect mode forced convection solar dryer. Also, did an economic analysis for the commercialization of the developed dryer.
- The capital cost of the tested dryer was 50,000 (INR), and the life of the dryer was taken as 20 years.
- Thermal efficiency of the solar dryer was 34.1% and 5.7% for the OSD.
- Ascorbic acid, total chlorophyll content, and color were better in the solar dryer.
- Payback period was found as 604 drying days.

The essence of true knowledge is to help the needy….

THANK YOU