Study of solar dryer technologies for Agricultural Produce

DDP Stage zero report
by

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Abstract

Solar drying is one of the cheapest and most effective method of food preservation and to cut down the cost in storage and transport. It is an essential part of agriculture for many crops, however, the most common method of open sun drying (OSD) results in significant crop losses due to direct exposure to environment. This presents a need for solar drying technologies which could overcome the challenges of open sun drying. Here, a review of drying principles and theories are presented. Basic terminologies around solar drying are discussed. Different drying strategies and classification of solar dryer based on construction, operating condition and operating mode are presented along with their advantage and disadvantages. The requirement for drying and general mehtod of drying and for some major crops are also discussed. Further the issues with the existing dryers and their potential solutions are also explored.

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Chapter 1

Introduction

Drying is essentially a simple process of moisture removal from the product. It could be done in many ways like shaking, freeze drying, heat drying etc. with an ultimate goal of separating moisture from the product. Drying process is very essential for the agricultural industry because it reduces the weight of product which makes it more transportable. It also enhance the shelf life perishable items.

In India major crops are primarily cultivated in tropical humid climate such as near monsoon or in a region with relatively higher humidity. This high humidity coupled with sudden rain and encroachment by the rodents, birds and insects are the major reasons for the crop loss in India. This is the primary reason for loss due to prevalent use of open sun drying in India. The use of drying technology could potentially resolve this issue.

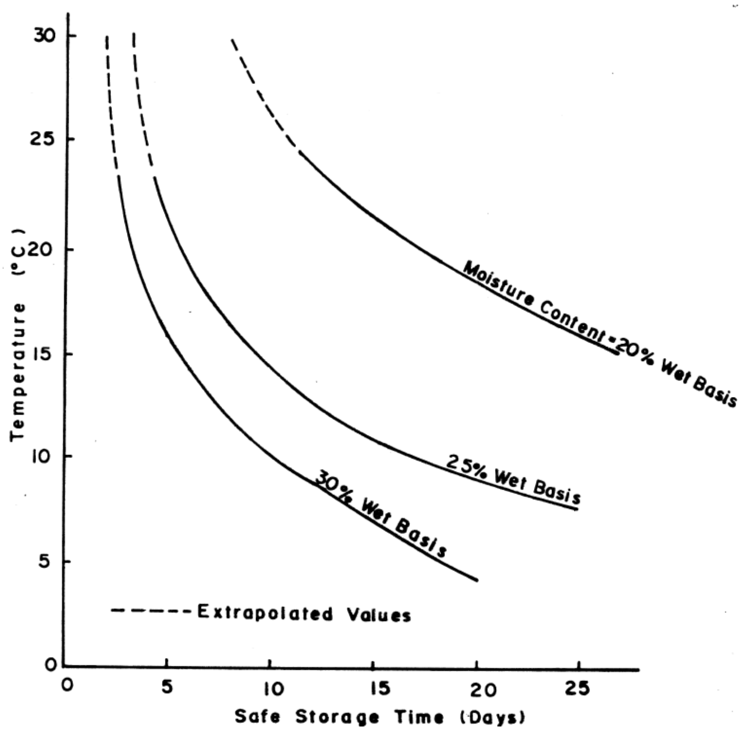


Figure 1.1: Safe storage period for corn (Ekechukwu, 1999)

Conventional drying system usually categorised based on operating temperature ranges. In lower temperature dryers the drying is predominantly brought by the constant ventilation where dry air removes the moisture from product. Where as high temperature dryers use active energy to evaporate the moisture from product which often leads to fast drying.

Being a diffused source of energy, Solar drying could be categorised as low temperature drying. It has many advantages such as zero running cost low complexity. It is also the cheapest method of drying and it has been throughout the world since millenia.

1.1 Objective

Objective of the current document is to present a review of the existing solar drying technologies, their classification and design and present a comprehensive view of the current scenario in the solar drying based on types of crops and location of its cultivation. Ultimatly, the aim of the document is to explore the research gaps in the existing literature.

1.2 Structure of document

The whole document is divided into four main parts. First chapter deals with the science of drying and introduces various concepts in the literature. The second chapter talks about the various technology currenly in place used for the solar drying purpose, it introduces classification of solar dryers their advantage and disadvantages along with their modifications that are currently being used in real-life. The third chapter tries to relate the existing technology in place with the crops and provides a broad picture of different requirements of crops. The fourth chapter concludes the key finding and provides direction for the future work.

Chapter 2

Drying

Drying methods of a particular crop is highly specific based on the desired outcome. During drying a crop many variables are controlled for a good market viability of the produce.

1. Quality of the final product : Many physical and chemical changes happens in a product during the drying process. The changes in size, colour, shape, textrue etc. are few which are easily observable. Other changes might include the change in nutritional values, taste, storage time etc. These changes are often desirable however use of inadequate drying techniques can often lead to non-markatable products.

   This makes the selection of specific drying technology very essential, since these changes are often governed by temperatue, air flow, direct solar radiation exposure and other parameters which varies widely between different drying technology. (Leon *et al.*, 2002)

   Heat transfer occurs from air (heating source) to the product.

2. Mass transfer happens where water from inside the product to the surface where it is evaporated to be carried away by surrounding air.

All the evaporation occur from the surface, hence the rate of drying strongly depends on the type of surface.

2.1 Thermodynamics

Thermodynamics of drying process is governed by both external and internal properties of product. Heat from the surface of the product is transferred from the air by convection and also through radiation of sun. This heat is used to increase the temperature of the product and surrounding air as well as evaporation of moisture from the produce. The moisture from inside the surface diffuses towards the surface to replenish the moisture at surface. Water vapour is continuously removed by the surrounding air. The drying depends upon the type of material to be dried. For non-hygroscopic materials the drying could be carried out till zero moisture level. While for hygroscopic material (most of the agricultural produce falls under this category) will have residual moisture level available trapped inside the product. In such cases high temperature is more effective in removing the moisture than high amount of air flow.

2.1.1 Drying parameters

External parameters includes:

1. Dry bulb temperatureT_{db}: It is the temperature of moist air indicated by an ordinary thermometer.

2. Wet bulb temperatureT_{wb}: Temperature of moist air measured by normal thermometer with wet wick over the bulb.

3. Dew point temperature: The temperature at which the condensation of water starts from air.

4. Relative Humidity (ϕ): Ratio of mole fraction of water vapour in the air with the ratio of saturated water vapour in the air.

$$\phi = X_w/X_{ws} \tag{2.1}$$

5. Humidity ratio (W): Ratio of weight of water with the weight of the dry air.

$$W = (18/29) * (X_w)/(1 - X_w) = 0.622(X_w)/(1 - X_w) \tag{2.2}$$

6. Enthalpy of moist air: Specific heat of air with water vapor content in it.

7. Pshychrometric Chart

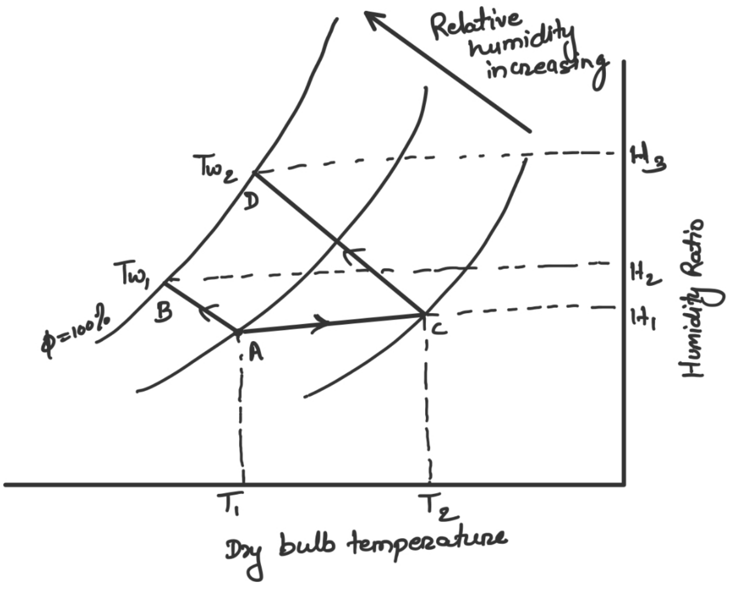


Figure 2.1: Schematic diagram for Pshychrometric analysis of drying

It is a relation between temperature and humidity of the air. As shown in Figure 2.1 the product currently at A will move towards B untill the air reaches to 100% relative humidity. Air will become saturated and cannot carry anymore moisture and drying will stop. Total amount of moisture removed from the product in this case will be $H_1 - H_2$. While when the air is heated to point B, then drying could occur till point D with net drying of $H_3 - H_1$ which is a larger amount of drying than without heating.

Properties of Product includes:

1. Moisture Content: It is the moisture present inside the product. It is expressed in percentage of moisture per wet matter or dry matter.

   Wet basis (M_w)

$$M_w = (w - d)/w \tag{2.3}$$

   Dry basis (M_d)

$$M_d = (w - d)/d \tag{2.4}$$

2. Equilibrium Moisture Content(M_e): The moisture content at which rate of moisture loss from the product equals the moisture gain from surrounding air.

3. Sorption isotherm : It is a curve of Moisture content vs humidity in surrounding air. It represents the hydroscopic state of products.

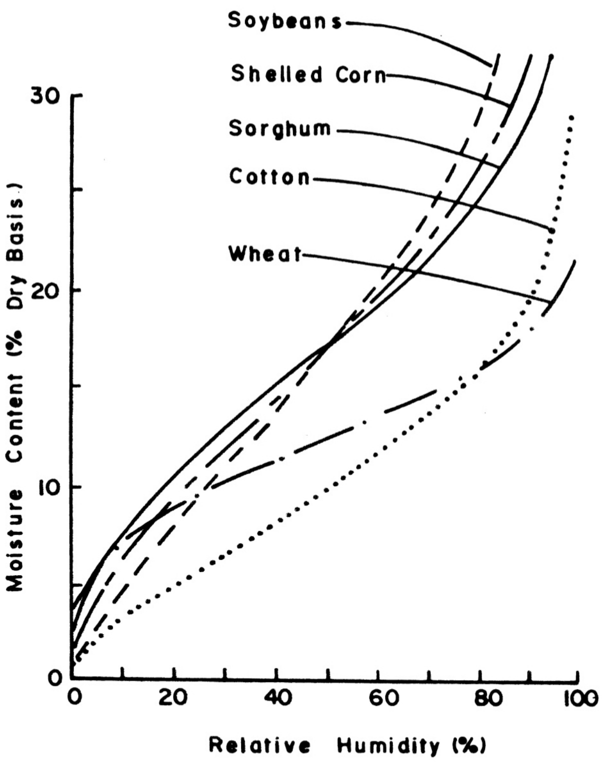


Figure 2.2: Sorption isotherm for different products (Ekechukwu, 1999)

2.2 Drying Strategies

2.2.1 Thin Layer Solar Drying

This strategy refers to drying a product where the entire surface of the product is exposed to the air. The migration of moisture of from the product follows the falling-rate regime similar to Newton's law for heating or cooling.

$$dM/dt = -K(M - M_e) \tag{2.5}$$

2.2.2 Deep Layer Dying

This strategy refers to drying of a bulk of product together where only certain amount of product is exposed to the air. Here hot and dry air is passed from one side which picks up the moisture content and product gets dry. The drying in this case is usually confined to a specific drying zone shown in Figure 2.3. Product at downstream (in the direction of air movement) from the direction of drying zone is damp and at upstream it is dry. The products in the dried regions have a very high risks of over-drying. The risk of over-drying increases at the initial layers with the increase in bed depth of bed. It is usually recommended that thickness of bed Should be less than 0.45 m if the temperature for drying to be employed is 45 degree C. (Malik *et al.*, 1987)

Figure 2.3: Schematic diagram of Deep layer Drying

2.3 Mechanism of Drying

Drying agricultural produce is very different than other frequently dried products at industrial level such as cloth and paper. Agricultural products are hygroscopic in nature where moisture present within the product is trapped in closed capillaries. Drying till zero moisture is possible only in non-hygroscopic materials, as in hygroscopic materials there will always be some residual moisture.

2.3.1 Drying regimes

There are mainly two drying regimes when it comes to drying:

Constant rate of drying regime

During this period the process of drying that takes place is simply the evaporation of water from the free water surface. It is represented in Figure 2.4 from B to C. The region in the Figure 2.4 from A to B shows the time to reach till the drying temperature. At contant drying region the rate of evaporation or the moisture removal primarily depends upon the ambient condition rather than the product. The surface of product is saturated with water.

Drying for non-hygroscopic materials happens in this region only. The end of this phase is marked by decrease in the rate of drying when the rate if moisture migration from inside the surface of product is less than the rate of evaporation. The moisture content at this stage is called critical moisture content.

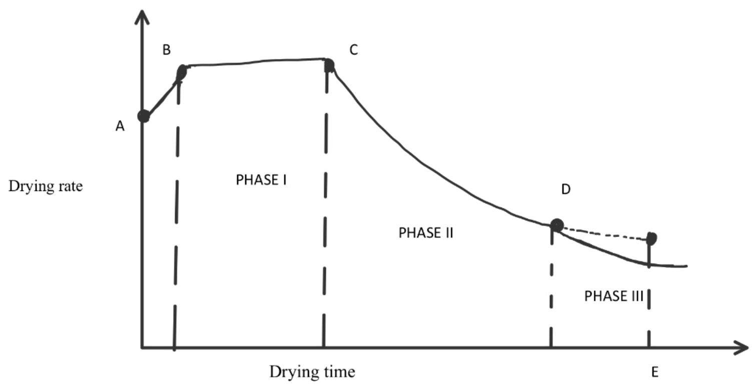


Figure 2.4: Schematic representation of drying rate at different regimes

Falling rate of drying regime

When the migration of moisture from within the product equals to the maximum rate of evaporation from the surface then critical condition is reached and drying occurs till the equilibrium moisture content is reached. Below the critical moisture content the rate of drying tends to decrease and it is dependent upon the rate of diffusion of moisture within the product which depends upon nature of product.

This stage is generally subdivided into two substages:

1. The first part of this falling drying rate period is related with unsaturated surface drying
2. The second part is where the diffusion process further slows down and determine the drying rate.(Malik *et al.*, 1987)

The falling period concerns the hygroscopic products. Majority of products stops before reaching the second substage.

Many products doesn't show the constant drying rate period since their natural/initial moisture content is close to critical moisture content.

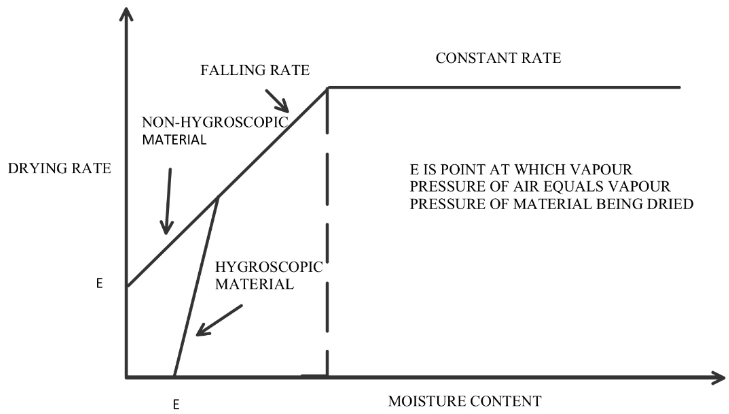


Figure 2.5: Drying rate variation with moisture content (schematic only)

2.4 Open Sun Drying

Open sun drying refers to drying crops open to air in direct sunlight. Crop losses and degradation are greatly influenced by the exposed local climatic condition. The open sun drying can be used if a climate is warm and dry.

This techniques used in this method is practically unchanged since its early prehistoric times. It can be divided into two categories:

1. Outdoor drying with direct sunlight exposure.
2. Drying with a plastic sheet or cover to protect from insects and rain. (Mustayen *et al.*, 2014)

It is the most common type of drying practiced in developing countries. It is usually practiced as grain, vegetables and fruits are spread on the ground exposed to direct sunlight for drying. Many types fruits needs direct sunlight for ripening and colouring. In some cases the harvest is left on the tree to fall on the ground and dry in-situ, this method have a clear advantage in terms of low cost and labour but also incur significant loss of produce and hygiene mainly due to contamination by:

- Dust and Debris
- Fungal Infection
- Insect infestation
- Bird and rodent encroachment
- Weathering effect

- Human and animal interference

Significant losses also occurs due to Degradation by overheating, intermittent sunshine, and interruption by rain. Simple remedy of this could be stretching a plastic sheet over the harvest which low cost but provides only marginal improvement, since the circulation of air is hampered. The method is specially unfit for deep bed drying, where non uniform drying is observed.(Malik *et al.*, 1987)

Despite of these shortcomings the open sun drying still remains the common method in use because of small capital cost, low running cost and independence from fuel supply, and these are often only commercially viable methods (Ekechukwu and Norton, 1999)

Advantages/Disadvantages:

1. There is no use of scientific methods : It is only based on the experience of the unskilled worker.
2. No control over the drying rate.
3. The rate of drying is slow as compared to other solar drying options.
4. The agriculture produce are generally sensitive to weather condition and during open air drying it is exposed to all kind of weather changes. This facilitates growth of microorganisms, degradation in quality and appearance.
5. It also leads to huge losses both qualitatively and quantitatively due to weather conditions, rodent attacks, infestation etc.

It is used for more than 80% of food produced by the small farmers in developing countries.(Belessiotis and Delyannis, 2011)

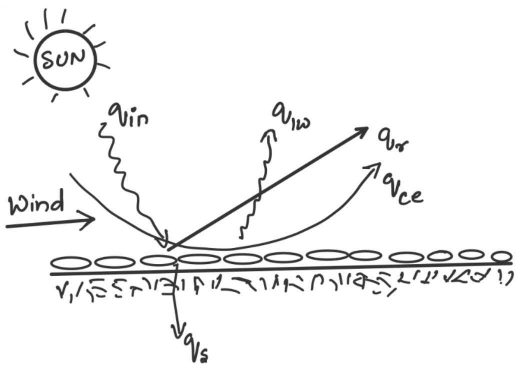


Figure 2.6: Schematic representation of Open Sun Drying

2.5 Models and equation

Few basic models related to drying were discussed by Belessiotis and Delyannis (2011)

2.5.1 The sorption equation

Water activity (α_w): It is defined as ratio of partial pressure of water solution with partial pressure of pure water.

$$\alpha_w = (p_w/p_w^*) \tag{2.6}$$

The water inside the agricultural products are essentially in form of solution hence the water activity is an important parameter for measuring self life, microbes growth etc.

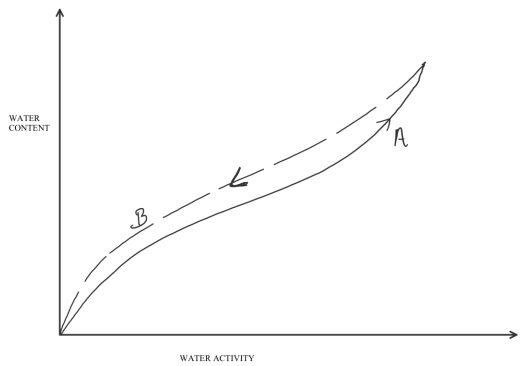


Figure 2.7: Sorption isotherm A: Absorption curve B: Desorption curve

The Figure 2.7 is similar to Figure 2.2 since both are sorption isotherms. There is a presence of small hysteria between absorption and desorption.

Langmuir (1918) proposed theory of absorption in layer on the material surfaces

$$\alpha_w\left(\frac{1}{X} + 1/X_{\text{mon}}\right) = \frac{1}{C \cdot X} \tag{2.7}$$

Brunauer *et al.* (1938) proposed modification in Langmuir equation for multilayer absorption in form of BET equation:

$$\frac{\alpha_w}{(1-\alpha_w)*X} = \frac{1}{X_{\text{mon}}*C} + \frac{C-1}{X_{\text{mon}}*C} * \alpha_w \tag{2.8}$$

The above equation was widely accepted for variety of products and was reliable in the range of $0.45 < \alpha_w < 0.50$ (Belessiotis and Delyannis, 2011) Modified BET equation by Brunauer (1945) for n layer :

$$X = \left[\frac{X_{\text{mon}} * C * \alpha_w}{1 - \alpha_w}\right] * \left[\frac{1 - [n+1] * \alpha_w^n + n * \alpha_w^{n+1}}{1 - (c-1) * \alpha_w - C * \alpha_w^{n+1}}\right] \tag{2.9}$$

The GAB equation proposed by Guggenheim (1966) is one of the most popular isotherm model. It is reliable to high range of $0 < \alpha_w < 0.99$

$$\frac{X}{X_{\text{mon}}} = \frac{C_{\text{b}} \cdot K \cdot \alpha_{\text{w}}}{(1 - K \cdot \alpha_{\text{w}}) \cdot (1 - K \cdot \alpha_{\text{w}} + C_{\text{b}} \cdot K \cdot \alpha_{\text{w}})} \tag{2.10}$$

This equation is just the modified version of earlier two isotherm models.

Chapter 3

Technology

Drying technology provides many benefits as compared to open sun drying methods: Few of which includes:

- Drying rate is higher than the open air sun drying
- Controlled drying could be achieved and optimised for individual products.
- Area requirement is greatly reduced since grains could be arranged and stacked in trays
- Losses are highly minimised since exposure to environmental conditions are reduced.
- Flexibility in design helps in the year long operation with modification based on different seasons and crops.

3.1 Solar Dryers

3.1.1 Classification

The dryers can be classified based on its design, operation, range etc.
Based on temperature range the solar dryers are divided into:

High temperature dryers

Used when rapid drying is desires and/or products can only be exposed shortly to the drying air. It have chances of over-drying, thus products are only dried to the required moisture content and then cooled. Because of the high temperature ranges, most designs are electricity or fossil powered. Only few practically-realised designs of high temperature drying system are solar-energy heated. (Ekechukwu and Norton, 1999)

Low temperature dryers

Here moisture content is usually brought to equilibrium by constant ventilation. It enables bulk crop drying and is most suited for long term storage. Low temperature dryers have ability to tolerate intermittent heat input which makes it most appropriate for solar-energy applications. Thus most practically realised solar dryer are low temperature dryers. (Ekechukwu and Norton, 1999)

The solar drying system can also be divided based on heating modes and way in which the heat is utilised:

1. Active Solar-Energy Dryers
2. Passive Solar-Energy Dryers

These could be further subdivided into three distinct sub-classes based on design and arrangement of components and mode of utilisation of solar heat:

1. Integral-type (Direct) solar dryers
2. Distributed-type (Indirect) solar dryers
3. Mixed-mode solar dryers

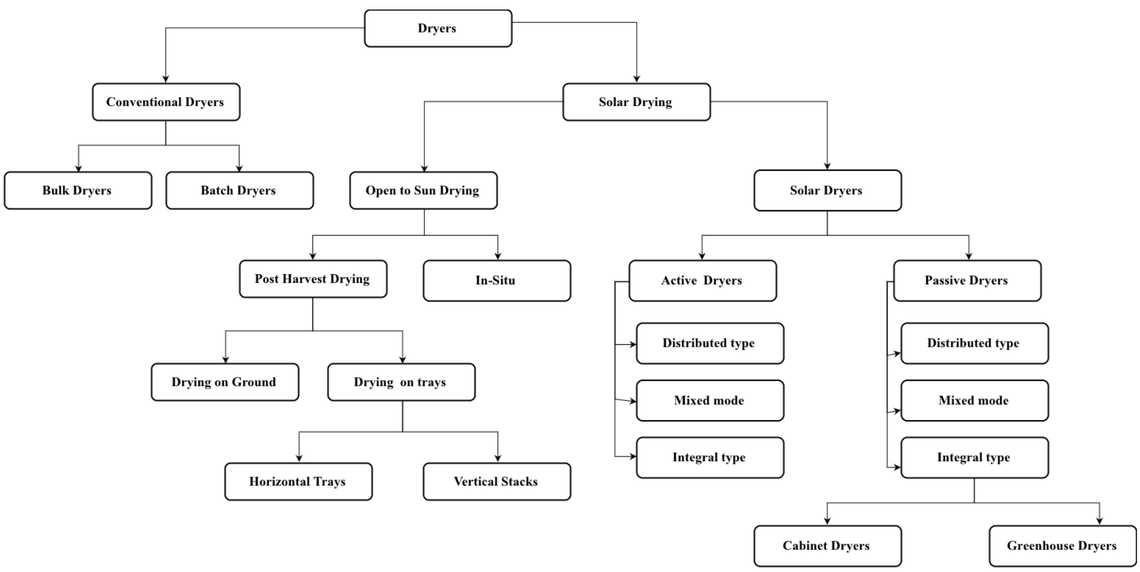


Figure 3.1: Different types of solar dryers

3.1.2 Passive Dryers

Passive dryers can be classified based into open to sun drying and natural circulation drying. Open-to-sun drying had been discussed in section 2.4.

These are also known as Natural Circulation dryers because it depends entirely on solar energy for its operation. These dryers are called passive due to absence of any moving parts. It also has lower cost compared to other alternatives, however the drying rates are limited. It is one of the most popular dryer due to low initial and maintenance cost with satisfying drying rates. It solve many problems with the open sun drying like dust, rain, insects, rodents etc. The component of passive dryers include transparent cover, a solar collector and drying chamber. If the collector and drying chamber is same, it forms integral (direct) type solar dryers and if it is separate is form distributed (indirect) type. Another category could be made by mixed type dryer where the separate solar collector as well as integrated solar collector and drying chamber is present.(Mustayen *et al.*, 2014)

Few advantages of natural circulation solar-energy Dryers includes (Ekechukwu and Norton, 1999)

1. Smaller area requirement as compared to conventional open to sun drying method
2. Low crop loss due to infestation, dust and fungi
3. Protection from rains
4. Low capital and maintenance cost due to simple design and use of local material for construction.

3.2 Active Dryers

Active dryers actively use other sources of energy along with solar for drying products. These dryers could be equiped with a mechanical fan or blower for circulation of air inside the drying chamber. It could also be integrated with electric or fossil fuel heaters to accelerate the drying process. The advantages of Active solar dryers over conventional dryers is the lower operating cost since it partly uses the solar energy as well. Due to the presence of a separate heating system other than solar, the control and reliability of active dryer increases as compared to passive drying system. Active dryers could be used for large scale drying as well as for sensitive drying.

3.2.1 Direct type dryers

Direct solar dryers is essentially an insulated box design with a transparent glass/-plastic cover and air holes for circulation of air. Solar radiation passes through the transparent cover and heats up the product as well as the box. The air inside the box heats up and pick up the moisture from produce and gets circulated via the air holes, this could happen naturally or by help of forced circulation (by fan, blowers etc.).

The incoming radiation will be partially reflected back to the atmosphere and a fraction of it will be transmitted to the box.

Direct solar dryers are simple in construction and cheaper in cost and it provides improvement from the open sun drying in terms of protection from dust, rain, infestation etc.

However the few notable drawbacks of direct solar dryers includes the overheating of products, limited capacity. The direct sunlight is also not suitable for many products which lead to discolouration however for few products this is desirable as it leads to the ripening of products (Ekechukwu and Norton, 1999; Mustayen *et al.*, 2014). In passive dryers the circulation of air is very low and there is an accumulation of moist air inside the dryer. This leads to condensation at the transparent surface since its temperature is often lower than the base of the box which affects the transitivity of the transparent surface.(Mustayen *et al.*, 2014)

There are two generic types of solar integral type passive solar dryers

Cabinet dryers:

It is small unit generally meant for smaller quantity of products to be dried. These insulated box with glass top provided for solar radiation. Air circulation is provided by the buoyancy forced through the apertures at the top of cabinet. Drying temperature could potentially reach up to .

Few recommended guidelines for provided by “Brace Research institute” are (Ekechukwu and Norton, 1999):

- The ratio of length and width should at-least be 3 to minimise the effect of shading from side panels.
- The glazing of the dryer is kept at its optimal angle for maximum performance. The optimum glazing angle is a function of latitudes.
- Wall should be dark coloured.

- The construction materials should be chosen locally.

The cabinet dryers are modified to enhance its performance which is reported extensively in literature by Ekechukwu and Norton (1999).

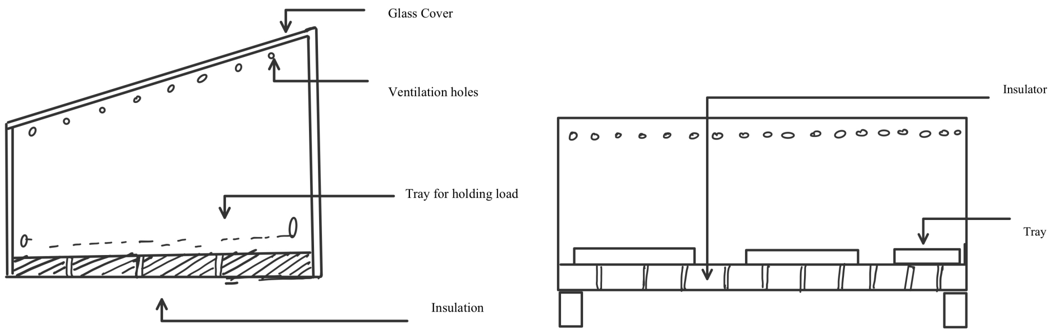


Figure 3.2: Direct cabinet solar drier with sloped and un-sloped glazing

Green house dryers:

These dryers are also known as tent dryers and the construction of these dryers are very similar to a green house. These are large dryers which are meant for large scale drying. The characteristic of these dryers are extensive glazing on the sides. Given the proper design of vent and their positions these dryers provides higher control of the drying process than the cabinet dryers for large scale drying.

3.2.2 Indirect type drier

Indirect solar dryers have a separated solar collector and drying chambers. First the air is heated and then passed on to the products. The hot air picks up the moisture from the produce and then removed from the dryer.

The performance of Indirect solar Dryers are better in fluctuating weather conditions and the investment is also low as compared to conventional dryers.

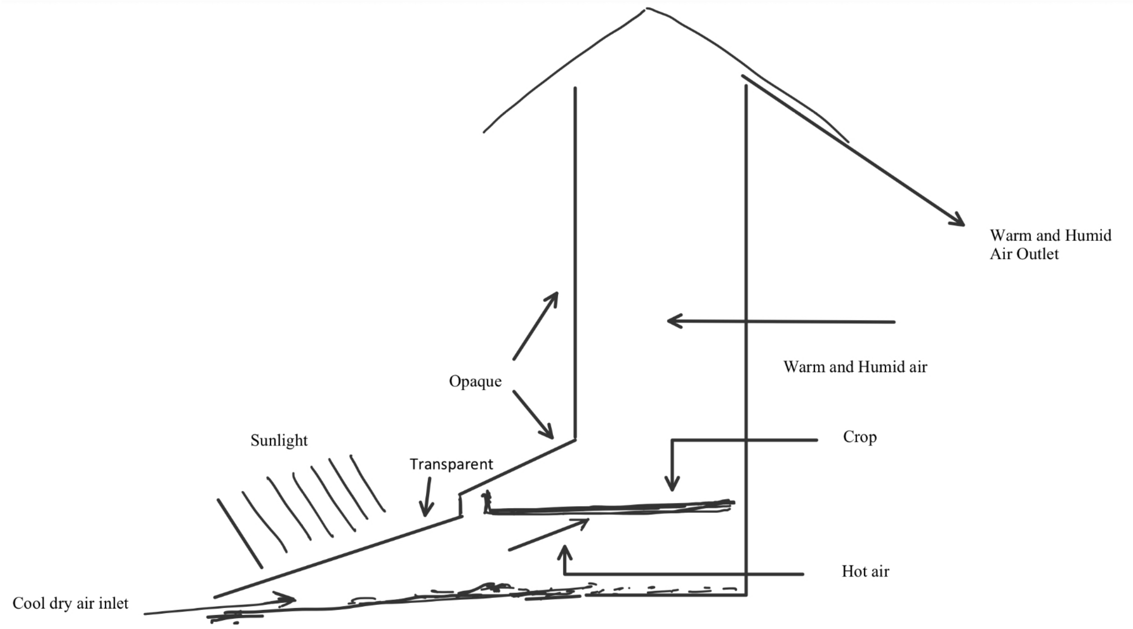


Figure 3.3: Indirect solar dryer

3.2.3 Mixed Dryers

Mixed type dryers contains the characteristics of both Integral(direct) type and Distributed(indirect) type solar dryers. Here the preheated air from from solar collector goes to drying chamber which itself is exposed to direct sunlight. This type of construction enhance the efficiency of the whole drying system but also inherit the disadvantages of both direct and indirect solar collector.

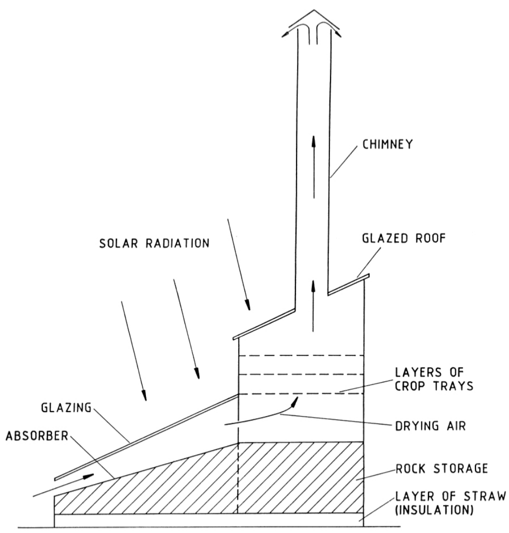


Figure 3.4: Mixed solar dryer(Ekechukwu and Norton, 1999)

3.3 More dryers

Apart from the basic classification there are several modifications of solar dryer present in the literature. These dryers are constructed for specific geographical location and the drying materials. Some modifications are discussed below.

Staircase Solar Dryers

This solar dryer has cabinets for the storage of crops in the form of stairs (see Figure 3.5). It provides certain benefits such as flexibility in terms of temperature, if something is to be dried at higher temperature, it could be kept at the higher stairs. The construction of this dryer is also very simple. the width of the dryer could be increased to accomodate more amount of drying materials.

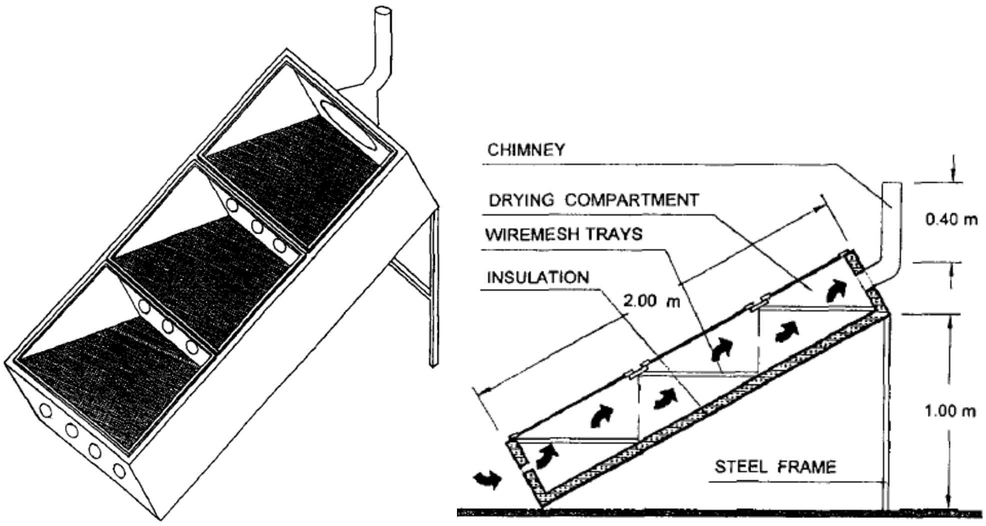


Figure 3.5: Staircase Solar dryer(Hallak *et al.*, 1996)

Shell type solar dryer

This solar dryer got its name based on its conical lower body design and shell like opening. The shell dryers are supplanted with the chimney and perforated trayes to facilitate the ventilation (Figure 3.6). Some time these are complemented with an gas ring to keep the temperature within the dryer constant.

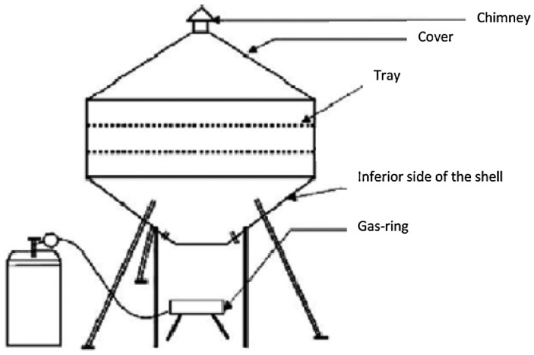


Figure 3.6: Shell type dryer(Bennamoun, 2011)

Green house solar dryer

These are also known as tent dryers. These are modifications of the green house dryers. A green house dryer is charecterised by the extensive glazing on the side and are often used for large scale drying. (See Figure 3.7). (Ekechukwu and Norton, 1999).

Based on structure these could be divided into two categories 1) dome shaped - which is used to maximise the utilization of solar radiation. 2) roof even shaped - which is used for proper air mixing in dryer. Based on mode of operation it could be either passive or active. (Prakash and Kumar, 2014)

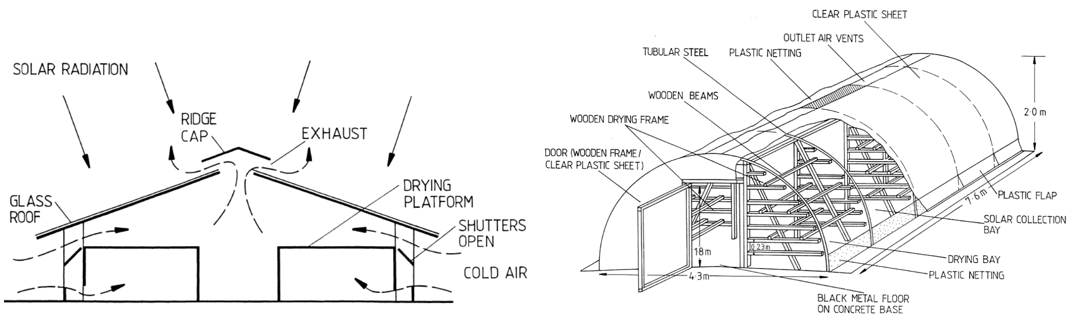


Figure 3.7: Roof and Dome green house Solar dryer(Prakash and Kumar, 2014)

Few other modifications of green house dryers were also reported by (Ekechukwu and Norton, 1999). From Figure 3.8 to Figure 3.11

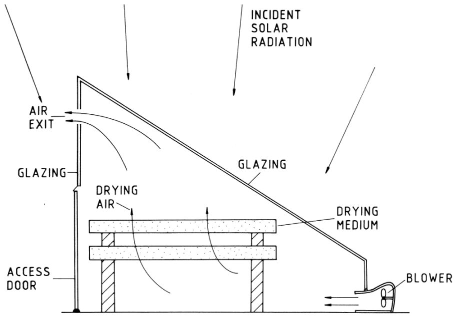


Figure 3.8: Forced Convection Green house Solar Dryer

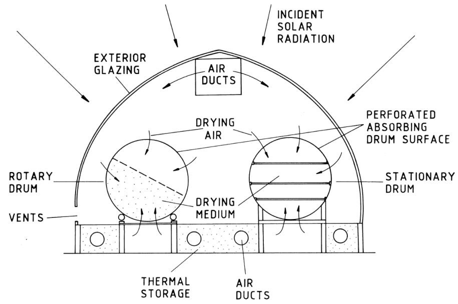


Figure 3.9: Interior drum absorber Green house Solar Dryer

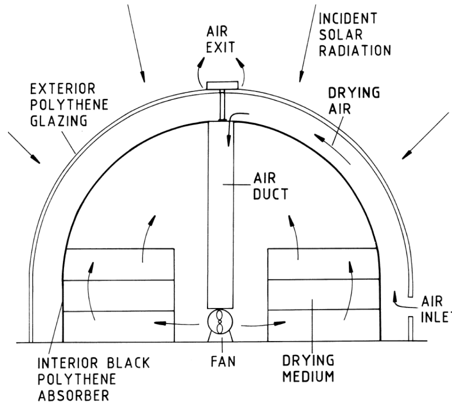


Figure 3.10: Interior plastic absorber Green house Solar Dryer

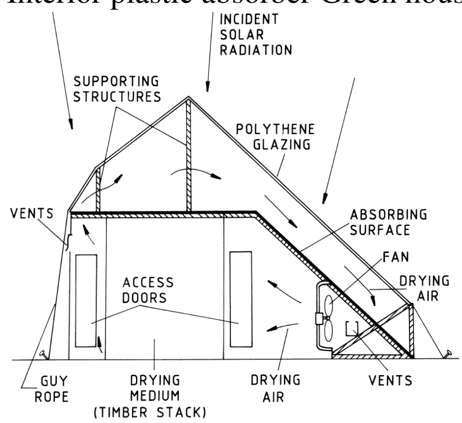


Figure 3.11: Interior absorber active Green house Solar Dryer

Reverse absorber solar dryer

This dryer is essentially a modification of cabinet dryer with a reflective surface added below with or without the upper glazing to increase the total amount of solar radiation. See Figure 3.12

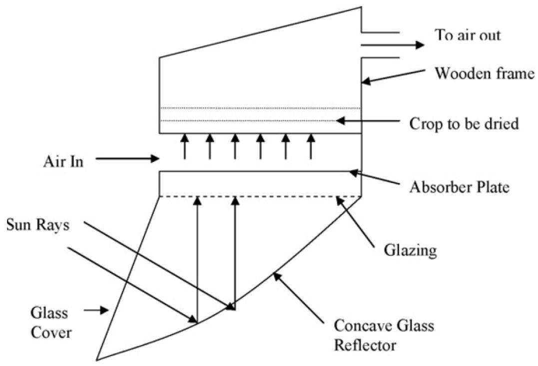


Figure 3.12: Reverse absorber solar dryer (Murthy, 2009)

Chapter 4

Requirements of crops

Drying methods of a particular crop is highly specific based on the desired outcome. During drying many variables are needed to be controlled for a good market viability of the produce. Many physical and chemical changes happens in a product during the drying process. The changes in size, colour, shape, textrue etc. are few which are easily observable. Other changes might include the change in nutritional values, taste, storage time etc. These changes are often desirable, however, use of inadequate drying techniques could lead to a non-markatable product.

This makes the selection of specific drying technology very essential, since these changes are often governed by temperatue, air flow, direct solar radiation exposure and other parameters which varies widely between different drying technology. Few qualities are mentioned below. (Leon *et al.*, 2002)

1. Sensory qualities: The value of the dried crop product is heavily dependend on the its sensory quality or how it appears. It is judged based on colour, texture, odour, taste, shape, size, uniformity etc.

   Crops could be divided into three groups based on its general flavours (Leon *et al.*, 2002):

   (a) Volatile flavours: such as onions

   (b) With non-volatile flavours: such as pea, beans etc.

   (c) With both volatile and non-volatile flovours (carrot and other roots)

2. Nutritional values: These includes amount of several chemicals such as sugar content, vitamins, acidity content etc.

   (a) Contamination by dust could result into high amount of ash content.

(b) High amount of sugar indicates higher drying temperatures and hence lower quality product.

(c) High acidity could potentially attributes to fermentation and detoriation and thus a lower quality produce.

(d) Lower vitamin C signifies nutrient losses due to drying for a prolonged period of time at a higher temperature.

3. Rehydration: The quality of product to regain its original quality such as its flavour, texture and appearance when water is added. However, it is very difficult for the products to regain its original moisture content completly. The closure to the original moisture content the better is the percieved quality of the product. The extent of rehydration is called rehydration capacity. (Oliveira and Ilincanu, 1999)

4.1 Common crop parameters

The table below provide some common physical phenomenon of crop drying.

Table 4.1: Moisture content (wet basis) of several agricultural produce for solar drying. (Fudholi *et al.*, 2010), (El-Sebaii *et al.*, 2002) and (Purohit *et al.*, 2006)

Crop	Moisture		Max. Temp (in degree C)	Drying time(h)
	Initial(%)	Final(%)		
Onions	85	6	55	48
Onion flakes	80	10	55	24
Onion rings	80	10	55	
Tomatoes	95	7	60	36
Peas	80	5	60	9
Grapes	80	15-20		32-40
Apple	82	11—14	65-70	24-26
Figs	70	20	70	32
Bananas	80	15	70	15
Cas sava	62	17		
Copra	30	5		
To bacco	90	10		96
Coffee	65	11		288
Garlic	80	4		48
Chilies	80	5		48
Ginger	80	10		168
Cabbage	80	4	65	48
Tea	80	3		96

Pepper	71	13		48
Turmeric	80	10		120
Potato chips	75	13	70	72
Paddy. raw	22-24	11	50	
Paddy. parboiled	30-35	13	50	
Maize	35	15	60	
Wheat	20	16	45	
Millet	21	4		
Corn	24	14		
Rice	24	11	50	
Cauliflower	80	6	65	
Carrots	70	5	75	
Green beans	70	5	75	
Garlic	80	4	55	
Cabbage	80	4	55	
Sweet potato	75	7	55	
Red lauan	90	20		
Potatoes	75	13	75	
Spinach	80	10		
Prunes	85	15	55	
Apricots	85	18	65	
Peaches	85	18	65	
Guavas	80	7	65	
Mulberries	80	10	65	
Okra	80	20	65	
Pineapple	80	10	65	
Yams	80	10	65	
Nutmeg	80	20	65	
Sorrel	80	20	65	
Coffee	50	11		
Coffee beans	55	12		
Cocoa beans	50	7		
Cotton	50	9	75	
Cotton seed	50	8	75	
French bean	70	5	75	
Groundnuts	40	9		

4.2 Spatial distribution of crops in India

For the development of a solar drying it is essential to look for the crop requirement as well as the environmental condition. India is a vast country spanning over multiple latitude, geographical regions, soil type and climate regions. Hence the geographical distribution of the crops are quite diverse. It is important to develop a technology with the place of use in mind, this provides several advantages other than optimising its performance such as availability of locally sourced material, easy repair and more resilience.

Below are few of the major crops and their drying stratergies are discussed from the literature. Cultivations maps of different crops are also provided which is generated based on the M/o Statistics & Programme Implementation (2013). Refer to A and B for further expalination of the data.

4.2.1 Paddy

Paddy is one of the most important crop in India and it is cultivated in nearly every region within India. Based on M/o Statistics & Programme Implementation (2013) highest number of agricultural households depends upon the paddy as their major crop. Most of the paddy is dried in-situ in open sun drying to reduce the labour and cost however, it results in significant losses. Moisture content of the rice grain should be below 14% to reduce any microbial activity(Salvatierra-Rojas *et al.*, 2017).

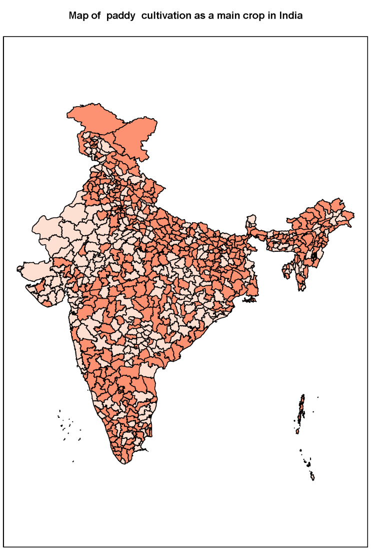


Figure 4.1: Paddy as major crop

4.2.2 Maize

Maize is also an important crop in India and it is cultivated in various regions within India. Use of solar biomass hybrid dryer for drying of maize and other characteristics of maize drying such as seed mortality, thermal cracking etc. are explored by Bosomtwe *et al.* (2019).

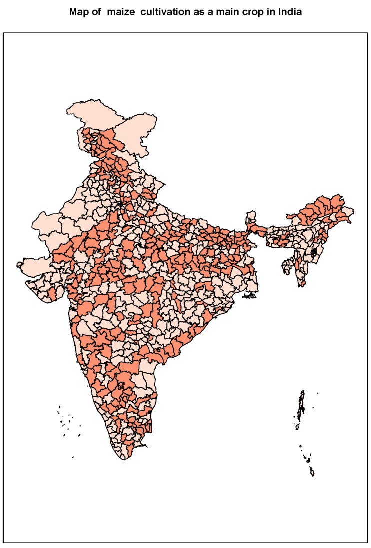


Figure 4.2: Maize as major crop

4.2.3 Onion

Onion cultivation is highly distributed within India (see Figure 4.3). India is one the major producer of onion in the world with a cosiderable amount of losses due to inadequate storage solutions. Kumar and Tiwari (2007) used green house dryers and found it to be more effective than the open sun drying based upon different drying coefficients.

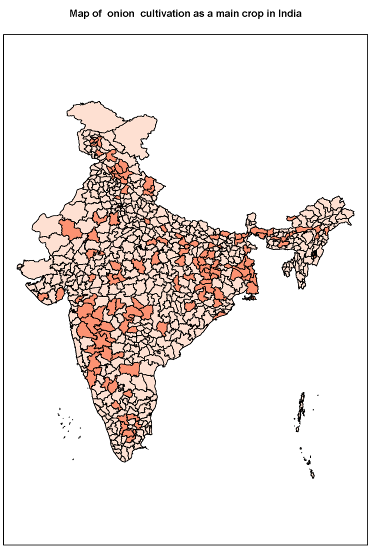


Figure 4.3: Onion as major crop

4.2.4 Potato

Potato is also one of the major crop of India, it cultivation is highly concentrated in the northern river plains in high fertility soil (see Figure 4.4). (Tripathy and Kumar, 2008) used mixed mode solar dryers to dry the potato slices.

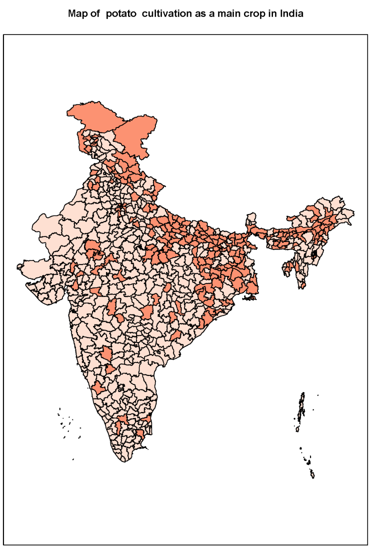


Figure 4.4: Potato as major crop

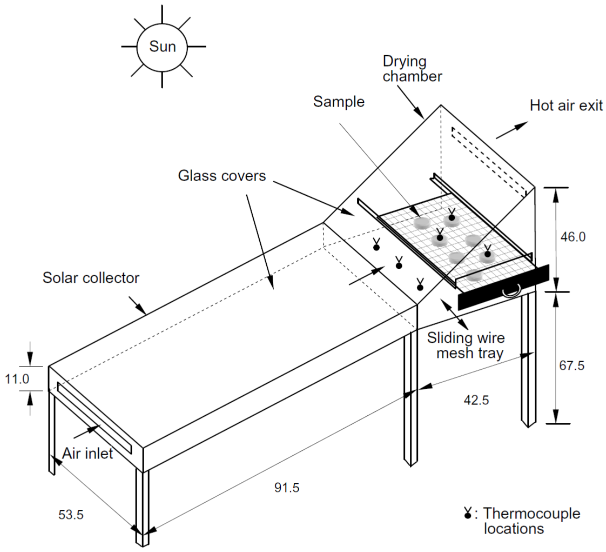


Figure 4.5: Schematic of experimental potato dryer (Tripathy and Kumar, 2008)

4.2.5 Mango

Mango is one of the most popular fruit in India and it is cultivated throughout India in different regions. Madhlopa *et al.* (2002) used the indirect dryer to dry the mango slices from 84% moisture content (w.b.) to 13% moisture content (w.b.) which retained its original flavour and 74% of the ascorbic acid content.

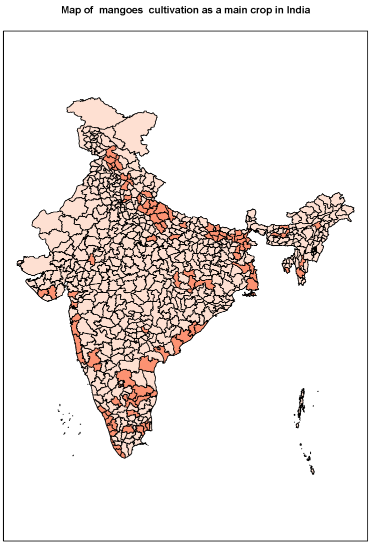


Figure 4.6: Mango as major crop

4.2.6 Tomato

Tomato contains high amount of moisture content (93% w.b.) and have a low shelf life. It is generally dried in slices. Tomato is also cultivated throughout India. Mango is one of the most popular fruit in India and it is cultivated throughout India in different regions. Sacilik *et al.* (2006) used the a tunnel dryer to reduce the final weight content of tomato slices to 11 % with 4 days of drying as compared to 5 days in open sun. Ringeisen *et al.* (2014) used concentrated solar reflecter dryer for the increasing the rate of drying to reduce the moisture content from 90% to 10% (w.b.) while reducing the drying time by 21% from open sun drying, however, no quality difference in the dried product was observed.

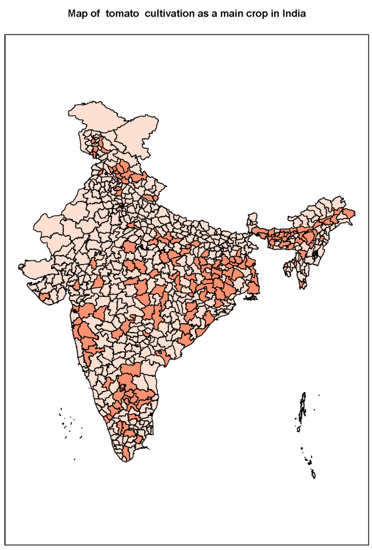


Figure 4.7: Tomato as major crop

4.2.7 Groundnuts

Groundnuts are extensively cultivated in India. Its a nutrient rich crop with high amount proteins and oils in its seeds. Safe moisture level for the groundnuts is 8-10 %. Sahdev *et al.* (2017) explores the indoor forced convection drying method for groundnuts and also discusses existing literature for groundnut drying.

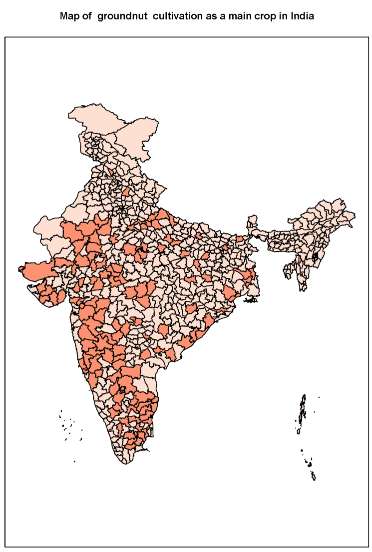


Figure 4.8: Groundnut as major crop

4.2.8 Chillies

Chillies are extremely sensitive to sunlight and get discoloured easily if it exposed to direct radiation. Hossain *et al.* (2005) discusses the issue of colour loss and try to optimise the solar dryer. These are generally dried in an indirect dryer.

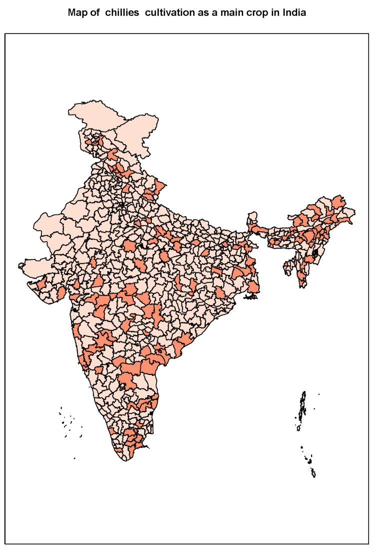


Figure 4.9: Chillies as major crop

4.2.9 Coconut

Coconut is commercial crop with high cultivation in southern India. It generally has 55-60 % of moisture content which is to be reduced to 6% for long term storage. Kulanthaisami *et al.* (2009) tests the solar tunnel dryer for coconut drying. They achieve the desired drying in 3 days as compared to 5 days in open sun drying (see Figure 4.10).

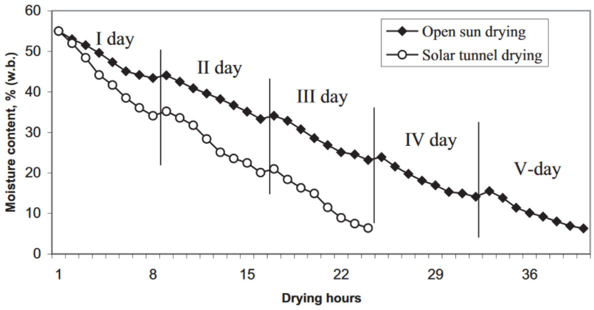


Figure 4.10: Variation of moisture content in coconut (Kulanthaisami *et al.*, 2009)

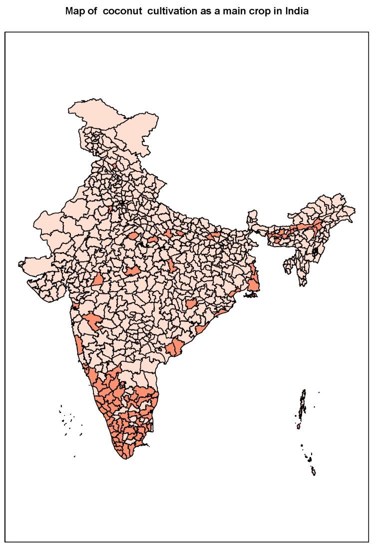


Figure 4.11: Coconut as major crop

4.2.10 Cotton

Cotton is also a commerical crop which is extensivily cultivated in the central India due to presence of suitable black soil in the region. Panwar *et al.* (2016) developed a thermal model for the solar tunnel drying of cotton.

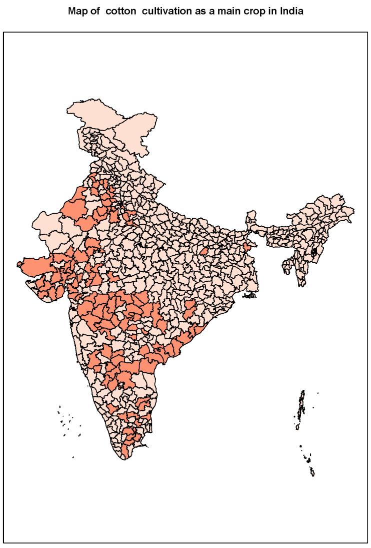


Figure 4.12: Cotton as major crop

Chapter 5

Current issues with solar dryers

Solar radiation has a strong diurnal cycle and seasonal cycle, this introduce uncertainty and limitation in the number of drying hours. This also results in fluctuation of drying air temperature which could be harmful for temperature sensitive crops. Solar dryers does seems to provide some control over different drying parameters. However the control of parameters requires active ventilation and constant measurement which adds to the capital. It also requires consant maintainance which needs expertise and adds to the cost.

5.1 Relation of drying with seasons

The other issue with the drying process that was not widely highlighted in the literature is tthe variation of solar irradiance and the amient air quality with seasons. Both absolute and relative humdity varies widely within the seasons. Both relative and specific humidity are higher within the monsoon and post monsoon months. Winters has the lowest absolute humidity but have higher relative humidity than from summers. See Figure 5.1 and Figure 5.2.

Similarly solar radiation also varies with seasons. Figure 5.3 shows a sharp difference in solar radiation between month of January and April, specifically in northern latitudes of India.

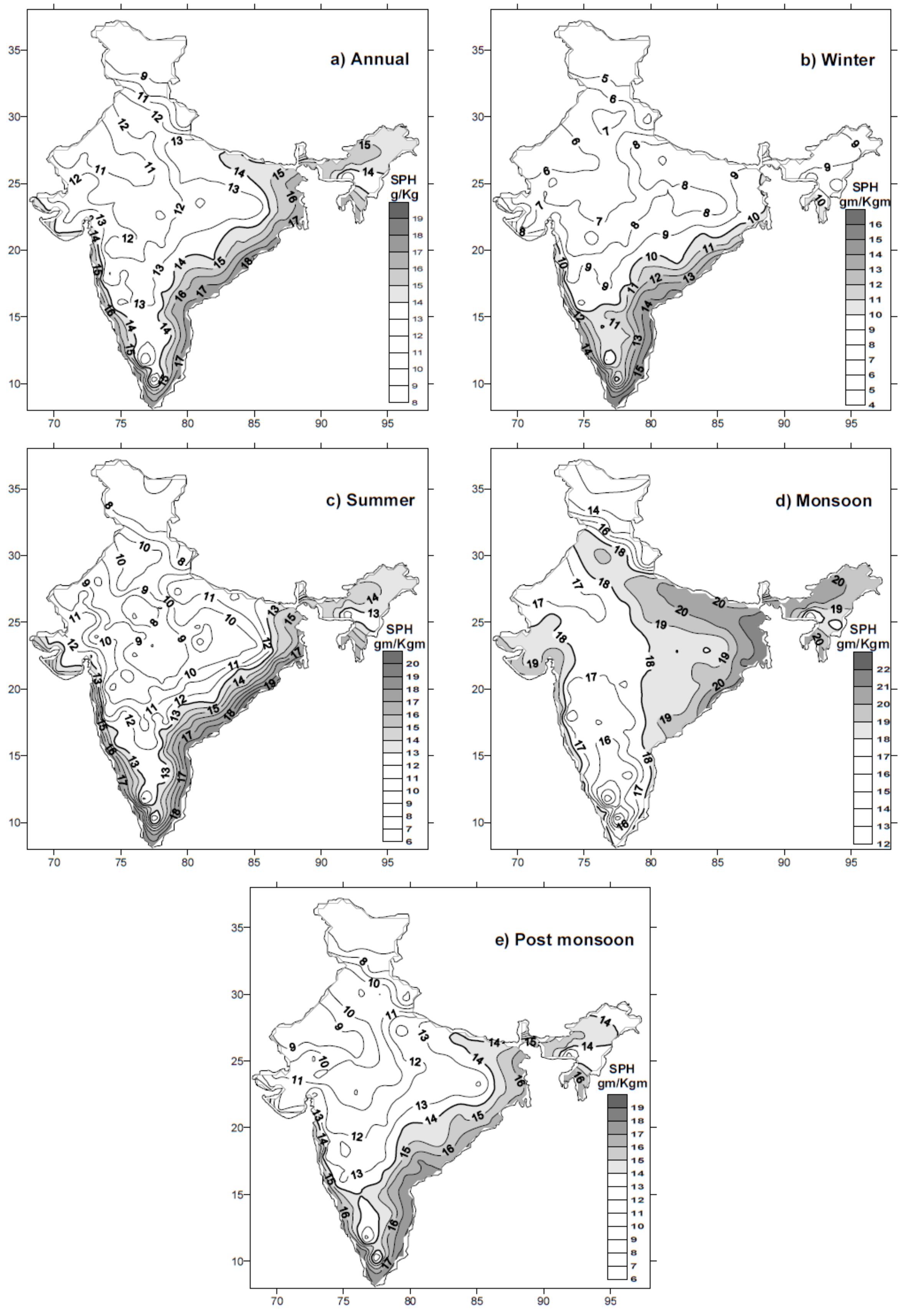


Figure 5.1: Spatial distribution of average specific humidty for period between 1971-2000 (Jaswal and Koppar, 2011)

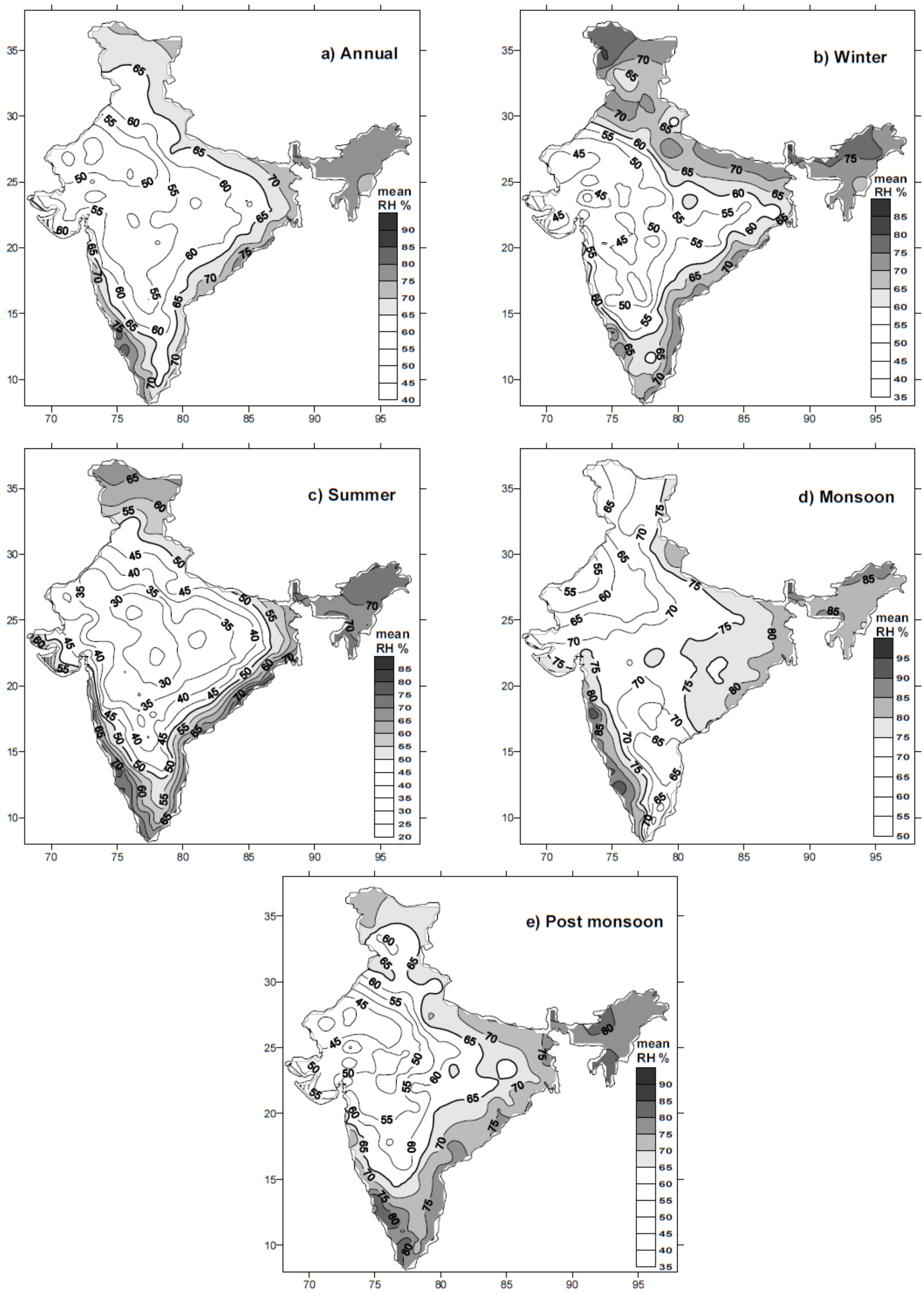


Figure 5.2: Spatial distribution of average relative humidty for period between 1971-2000 (Jaswal and Koppar, 2011)

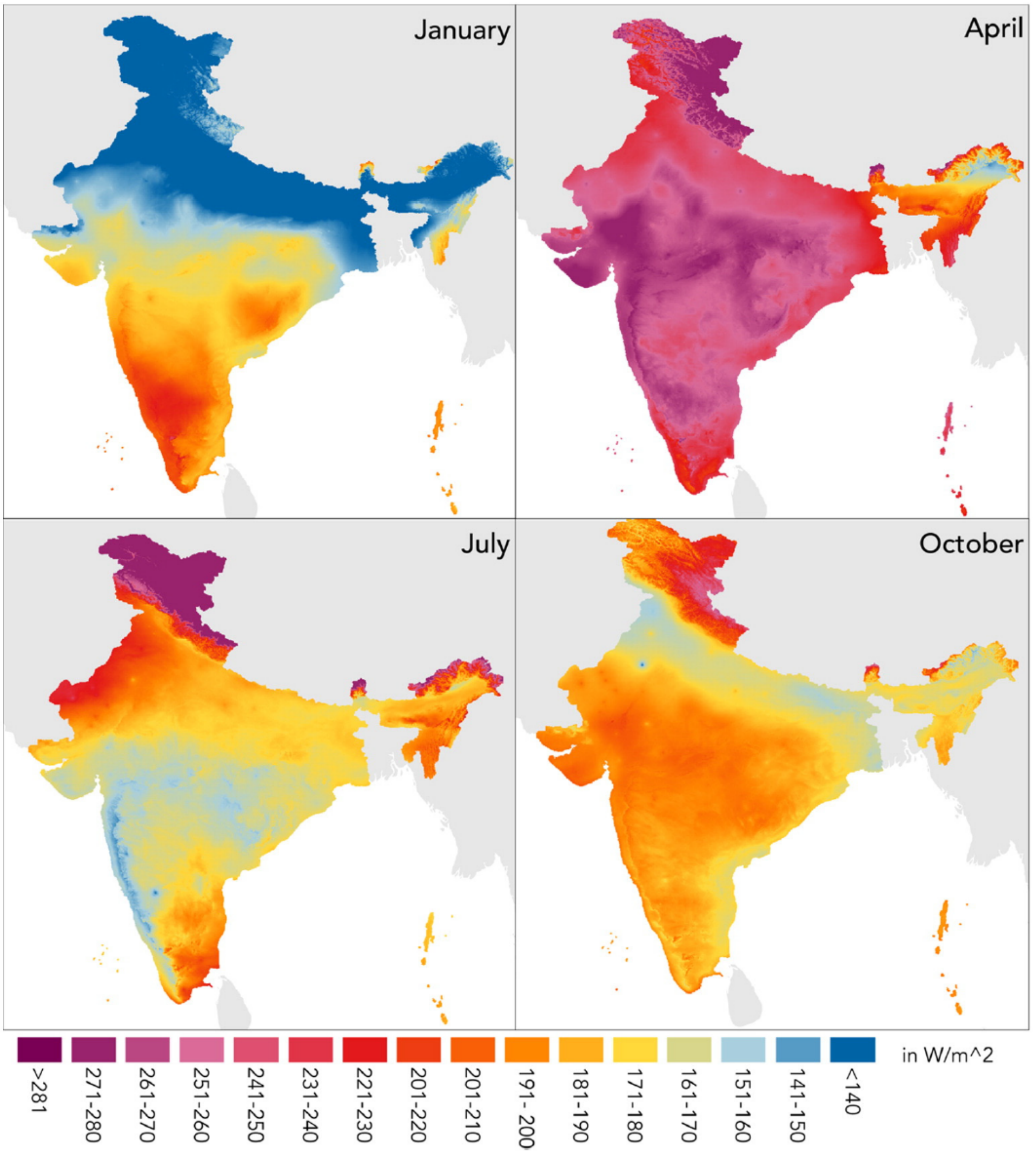


Figure 5.3: Mean Solar irradiance (GHI) for 1994 to 2014 (Müller *et al.*, 2017)

5.2 Integration of heat storage with solar dryers

This problem could be mitigated by integrating heat storage with the dryer, by storing extra energy durng the day to use later when sun is not available. There are mainly two kinds of heat storage options 1) Thermal storage and 2) Chemical storage. Thermal storage is further divided into i) Latent heat storage and ii) Sensible heat storage. Latent heat storage includes PCM (phase change materials) which has high heat storage capacity compared to sensible heat storage. Solar dryers with PCM heat storage are quite suitable for continuously heating the material at 50 – 60-degree C. (Kant *et al.*, 2016)

Few criterion for the suitable PCM for solar dryers are:

1. Operating/melting point at the desired temperature range
2. High heat density - both in terms of mass and volume
3. High thermal conductivity
4. Sharp melting point
5. Small change during phase transition
6. Chemically stable
7. Non-toxic, non-corrosive, non-flammable and non-explosive
8. Inexpensive
9. Easily accessible

Use of PCM and appropriate storage allows the user to dry the batch in continuous cycle and reduce the overall time of drying. There is less amount of literature available for the storage of energy during drying. There are many phase change materials currently used as heat storage for different crops such as Reyes *et al.* (2014) used paraffin wax for drying mushrooms in a hybrid solar dryer.

Berroug *et al.* (2011) used $CaCl2 \cdot 6H2O$ as a PCM for a green house dryer. Many PCM solar dryers were studied by the Kant *et al.* (2016) some of which are listed from Figure 5.4 to Figure 5.8

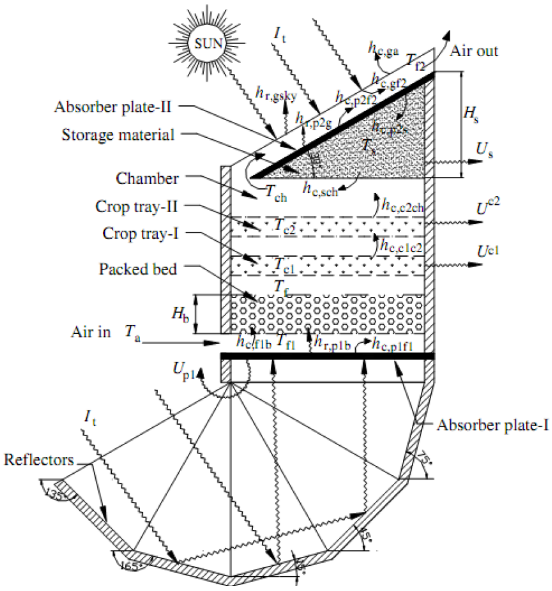


Figure 5.4: Reverse observer solar dryer with heat storage

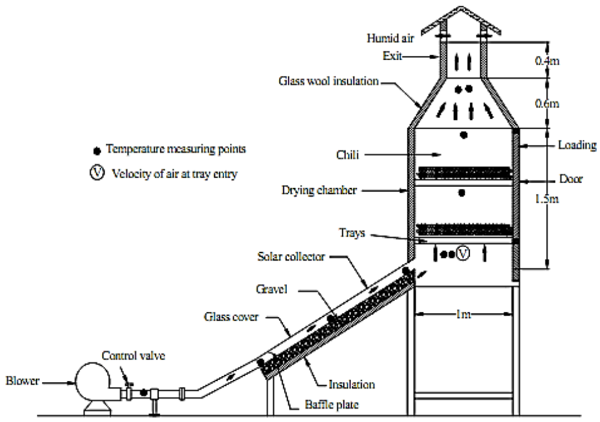


Figure 5.5: Indirect type PCM based active dryer

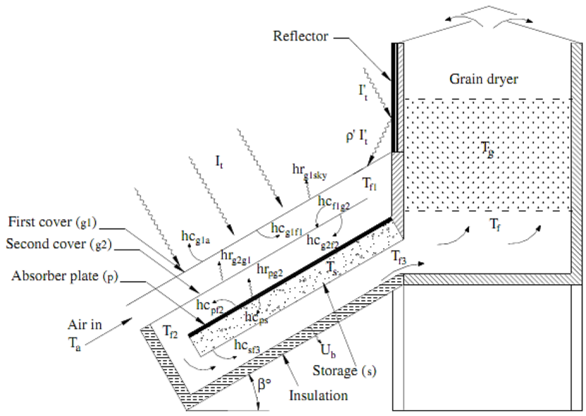


Figure 5.6: Deep bed inclined indirect drier with PCM

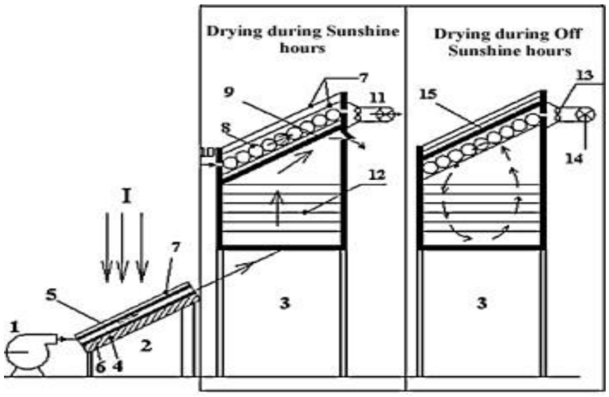


Figure 5.7: Desiccant based solar dryer

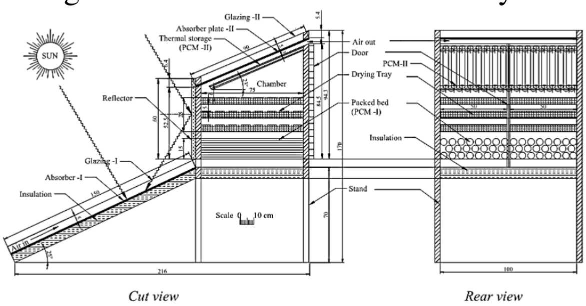


Figure 5.8: Flat plate mixed solar dryer with heat storage

Kant *et al.* (2016) also provides a list of several PCM materials with their properties which could be used for drying purposes.

Chapter 6

Conclusion and future Work

6.1 Conclusion

A review of theories and principles of drying has been discussed along with the classification of drying technology, their construction, advantages and disadvantages. Need of solar drying was also established. Isotherm absorption models in the existing literature were discussed. The spatial distribution of the crops that needs solar drying were also presented along with the technology that is generally employed for drying. Further the issues and their potential solutions in terms of use of storage and PCM were discussed.

For most part, the specificity of a crop is not very much developed with the design of dryers. Most of them are using the solar tunnel dryer (type of greenhouse dryer) as a generic solar dryer. In literature solar dryer has shown advantages over open sun drying in terms of reduction of losses, higher drying temperature, low drying time, higher quality and lower losses. But as mentioned chapter 4 each crops have a specific technology requirement. It doesn't allow the current technology to be used for broader range of crops and climatic conditions. chapter 5 highlights some of the issues and its solutions with the incorporation of PCM heat storage solution. There is need of a solar dryer which adresses the problems with the current design, which is easy to use, inexpensive and works in a broader range of conditions.

6.2 Future Work

Future work includes the study and development of PCM based dryer which could be used without or slight modification to a large number of crops. Also the economic and social aspect of the new solar dryer needs to be studied for designing a value generating equipment for farmers.

Appendix A

Code

Following is the code for generating maps of crop cultivation throughout the India at the district level. The was extracted from the survey conducted by M/o Statistics & Programme Implementation (2013). Further details about the data and few relevant maps are provided in appendix B.

```
crop <- readline(prompt = "Enter␣the␣crop␣name␣(Refer␣to␣the␣list):␣")
v1 <- read.delim(file = "v1_data.txt", header = FALSE)
v2 <- read.delim(file = "v2_data.txt", header = FALSE)

library(dplyr)

v1_clean <- v1 %>% select(V11, V23)

v2_clean <- v2 %>% select(V11, V23)

# merging the data
#       https://www.datacamp.com/community/tutorials/merging-datasets-r
#       https://www.statmethods.net/management/merging.html


merged_data <- rbind(v1_clean, v2_clean)
# Used to merge the two data sets.
# Since the data represent same thing - rows are simply added.

data_clean1 <- na.omit(merged_data)
```

```
# All NA removed
#       https://www.programmingr.com/examples/remove-na-rows-in-r/

data_clean2 <- distinct(data_clean1)

# remove all the duplicates

rm(data_clean1, v1, v2, v1_clean, v2_clean, merged_data)


crop_code <- read.delim(file = 'crop_codes.txt', header = TRUE, strip.white = TR
# Read the crop code
district_code <- read.delim(file = 'district_codes.txt', header = TRUE, strip.wh
#Similar thing to the district code
# Use strip.white to remove all the white spaces from the file

crop_code$Cases = NULL
crop_code$X = NULL
district_code$Cases = NULL
district_code$X = NULL

names(district_code) <- c("V11", "distname" )
names(crop_code) <- c("V23", "cropname" )
#changes the header

data_clean3 <- merge(district_code, data_clean2, by = "V11")
data_clean4 <- merge(crop_code, data_clean3, by = "V23")

data_clean4$V11 = NULL
data_clean4$V23 = NULL

data_parse <- split(data_clean4, data_clean4$crop)

# Parse the data and creates a list of lists with seperated out data

rm(data_clean2, data_clean3, data_clean4, crop_code, district_code)
```

```
crop_data <- data_parse[[crop]]

crop_data$crop_name[crop_data$cropname == crop] <- 1
crop_data$cropname = NULL
# Replace the crop name with number for easier plotting
names(crop_data)[2] <- crop
# changing the header

library(maptools)
library(rgdal)
library(RColorBrewer)
library(foreign)
library(classInt)


shp <- readOGR("Demographics_of_India.shp")
# To read the GIS shape file

dbf_raw <- read.dbf(file = "Demographics_of_India.dbf")
dbf <- left_join(dbf_raw, crop_data, by = c("distname"))
dbf[is.na(dbf)] = 0
write.dbf(dbf, "Demographics_of_India.dbf")
shp <- readOGR("Demographics_of_India.shp")
write.dbf(dbf_raw, "Demographics_of_India.dbf")
rm(dbf, dbf_raw, data_parse, crop_data)

colours <- brewer.pal(3, "Reds")
brks <- classIntervals(shp[[crop]], n=2, style= 'fixed', fixedBreaks = c(0,1

brks <- brks$brks

plot(shp, col = colours[findInterval(shp[[crop]], brks, all.inside = TRUE)],
box()
# Insert the map inside a box
title(paste('Map of ', crop, ' cultivation as a main crop in India' ))
# Insert title of the map

rm(shp, crop, brks, colours)
```

```
# Remove all the varibles
```

Appendix B

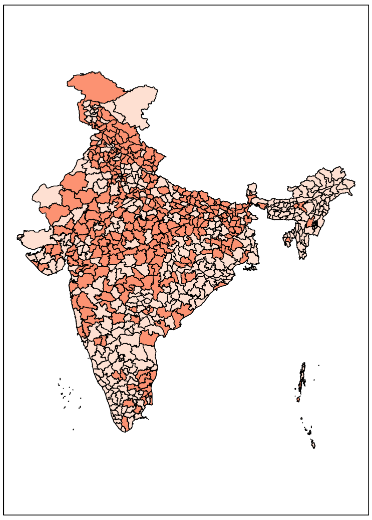
Maps of crop cultivation

The Ministry of Statistics and Programme Implementation, Government of India conductes several annual survey in many topics such as Industry, agriculture, households, land holdings etc. These data are pan India survey with very high level of granualarity - often till individual household level. The data that was used in the current document is a part of "India - Situation Assessment Survey of Agricultural Households, January - December 2013, NSS 70th Round". which was conducted in 2013 in two seperate visits and surveyed each household dependent on agriculture. The areas of interest were educational level, level of living, farming practices, possession of productive assets, awareness as well as access to modern technology in the field of agriculture, resource availability, indebtedness and a host of other relevant issue for the agricultural households.

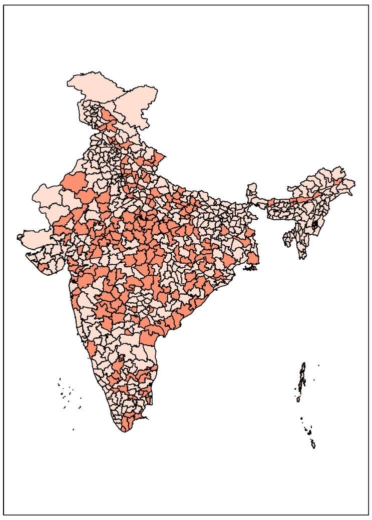
The current data sets were taken from Block 5a "value of output for the crops produced" during both visits and combined to make one data sets. Among the 38 different variables in block 5a the vaiable for the district code and crop code were chosen to map with the shape file extracted from ArcGIS hub for the "Demograhics of the India" from [https://hub.arcgis.com]. Since the data was at the hamlet level which is a strata within district level, all the hamlets within the same district were combined and the major crops within the district is presented with the code in R provided in appendix A.

Several other crop maps are provided below which has data density of more than 0.5% in the data set.

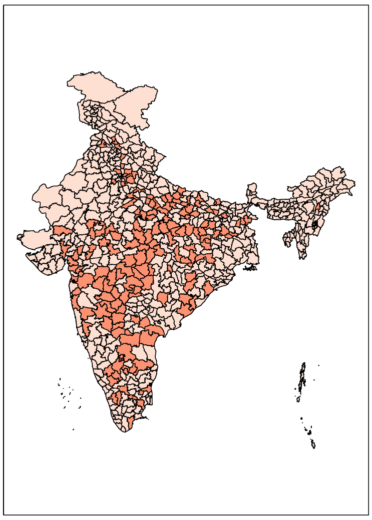
Map of wheat cultivation as a main crop in India



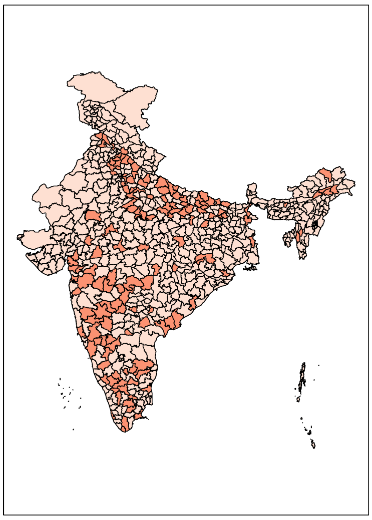
Map of urad cultivation as a main crop in India



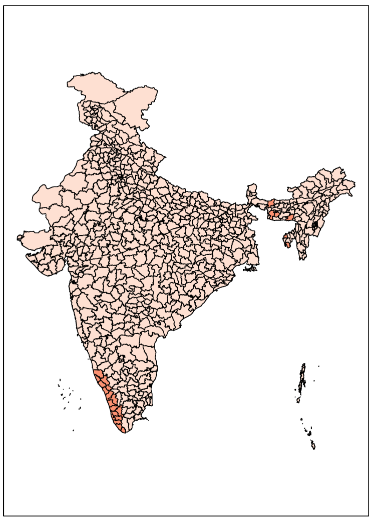
Map of tur cultivation as a main crop in India



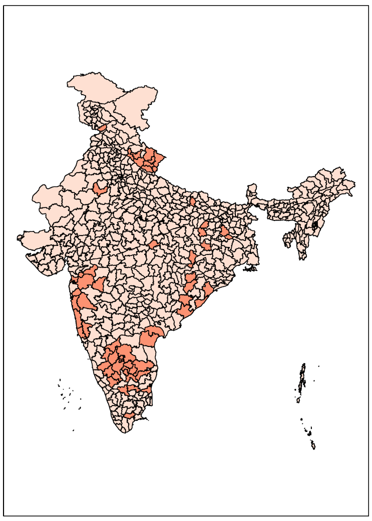
Map of sugarcane cultivation as a main crop in India



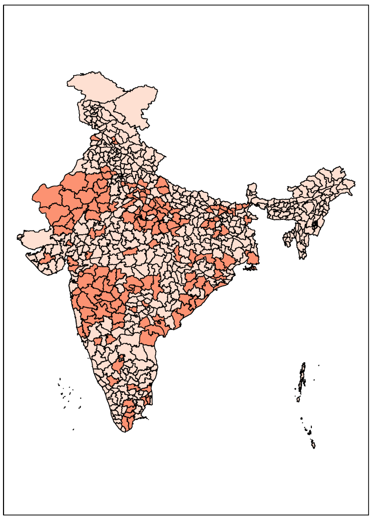
Map of rubber cultivation as a main crop in India



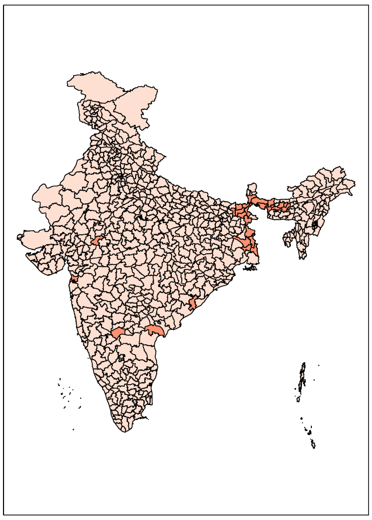
Map of ragi cultivation as a main crop in India



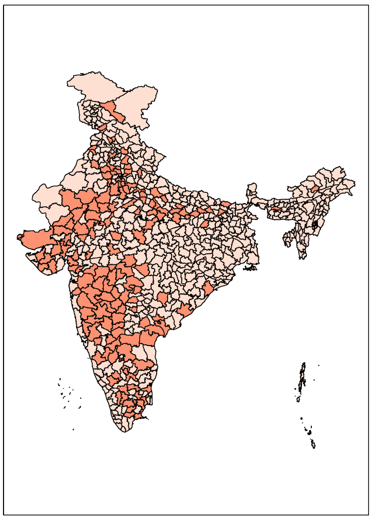
Map of moong cultivation as a main crop in India



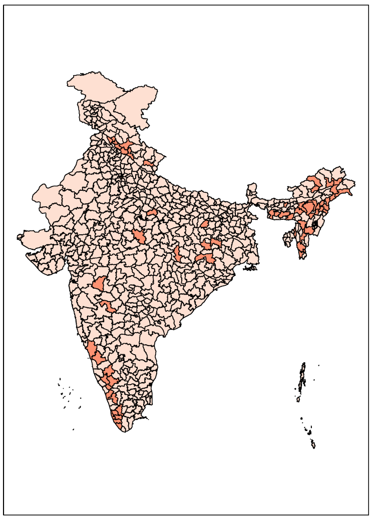
Map of jute cultivation as a main crop in India



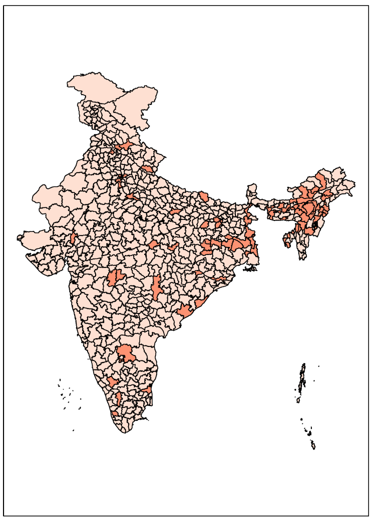
Map of jowar cultivation as a main crop in India



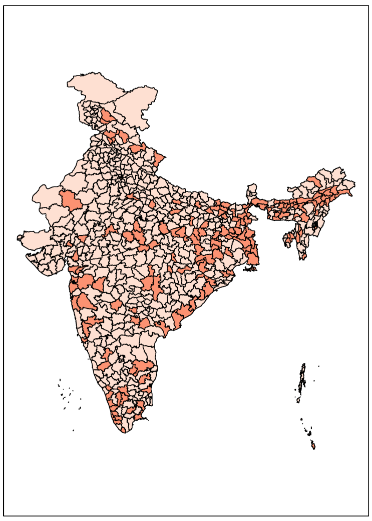
Map of ginger cultivation as a main crop in India



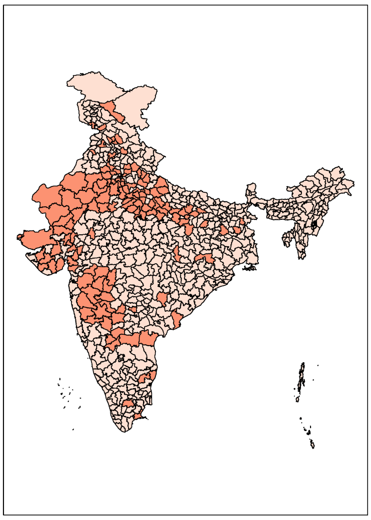
Map of cabbage cultivation as a main crop in India



Map of brinjal cultivation as a main crop in India



Map of bajra cultivation as a main crop in India



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