Design and Fabrication of Food Dryer

A Final Year Project Report

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

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ABSTRACT

Pakistan has two major national strengths; the high rate of agricultural production and the solar irradiance that graces most of the country year-round. This project attempts to combine the two with a complementary technology that would enable Pakistani food products to compete internationally by both improving quality and cutting costs. Microwave drying with Convection has been proven in literature to be a highly efficient method of drying food items. Microwave convective drying (MCD) is achieving growing interest for its distinctive volumetrically heating capability and ability to considerably cut back drying time and improve food quality. Long drying time may be a concern in food industries. We are innovating the system by carrying out the drying operation in a highly dehumidified environment which both in theory and practice, results in improvement in all desired control parameters.

ACKNOWLEDGMENTS

First, we would like to express our sincere gratitude to our project supervisor, Dr. Zaib Ali, for his support, supervision, and insights throughout the project. Working with Dr. Zaib Ali has truly been a pleasure which exposed us to plenty of research and enabled us to learn a lot about designing and manufacturing.

Special thanks to Muhammad Usama for being a crucial guide for us at the initial stages and helping us clarify the vision for our project and suggesting the necessary roadmap for putting things into practice.

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ABBREVIATIONS

MCD	Microwave convective Drying
RH	Relative Humidity
HD	Hot air drying
MWD	Microwave Drying
VD	Vacuum Drying
IRD	Infrared Drying

NOMENCLATURE

F_R	Collector heat removal factor
$F_R U_L$	Thermal losses of solar collector ((W/m^2)/°C)
$F_R(\tau\alpha)$	Conversion factor (optical efficiency of solar collector)
Ψ	Concentration
D	Diffusivity

CHAPTER 1: INTRODUCTION

Energy performance in manufactured goods' high-satisfactory and drying charge are three most important issues in food drying. Drying analysis evolved to optimize these three parameters. based on the market drying technologies, drying strategies are divided into four generations. 1st and 2nd inventions represent various convective drying techniques. Cabinet, kiln, belt, and conveyor drier are considered the first generation, and spray and drum drier is considered the second generation drying. Then freeze and diffusion drying are considered the third generation. Microwave and RF-connected drying are quoted as innovator and fourth-generation drying technology.

This report is structured to follow the scientific method. This flow chart of the scientific method acts as a north star to keep the structure of the study consistent and helpful This flowchart is proven in Figure 1.

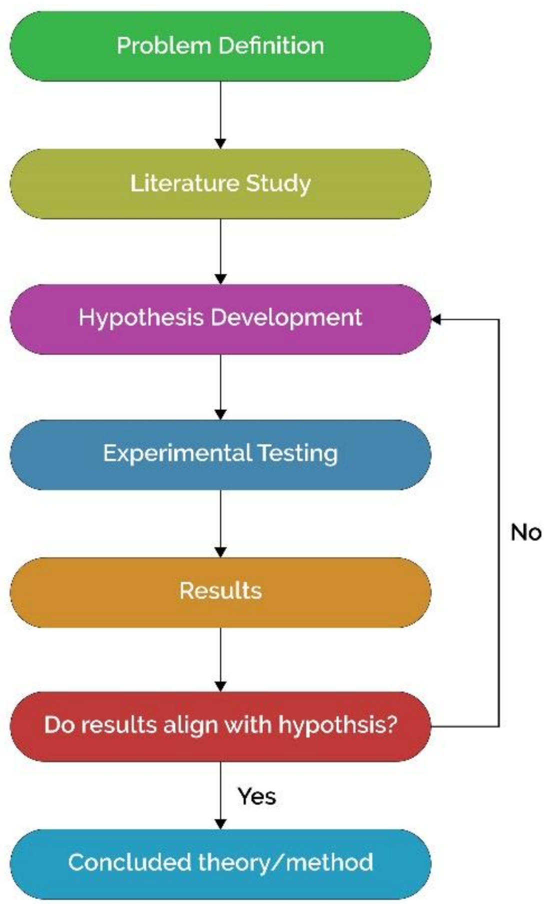

Figure 1 Flowchart of Scientific Method

The first step of the method is to ask fundamental questions:

Is food protection a main problem?

If so, why is food security a major issue?

Is dehydration of food a technique to relieve this problem?

If yes, what are bottlenecks preventing it from doing so?

The beginning of the paper concentrates on rationalizing that the question we expect to solve is reasonable. The introduction revolves around creating a concrete understanding of the core problem and establishing the solutions that are explored in this paper as suitable candidates to address said problems.

It is understood that 1/3rd of the food manufactured worldwide is squandered. The sinks of food wastage or loss differ based on the economic conditions of the countries, their weather conditions, agricultural status, logistical practices, and the behavior of end consumers. While most of the food waste in developed countries occurs after the food has reached its end consumer, maximum of the food loss in growing nations takes place even earlier than harvested food is picked up from the farm through transporters and later processed and sold.

Food loss generates 170 million metric tons of CO2 discharges each year [1] and is therefore considered a major threat to environmental sustainability. For scale, we would need 8.5 billion of adult trees just to absorb the negative global impact left on the planet by loss of food products and edible items each year [2].

This positions food loss as a problem in dire need of preservation methodologies and solutions.

These energy requirements, along with the capital cost of equipment used for food preservation forces farmers and producers in developing countries to opt for cheaper food preservation methods, which deteriorates food quality and fails to preserve massive quantities of post-harvest agricultural produce [24] [25].

Post-harvest food loss directly leads to increase in levels of nutrition deficiencies and global hunger [1]. And given that farmers in developing countries are the most ill-equipped to adequately preserve their post-harvest agricultural harvest, it arises those developing countries are also the most severely impacted by nutrient shortages in their people.

Given that the world population is estimated to reach 10 billion by 2050, food production would have to increase by 70% to meet global needs [1] and considering that one third of the food produced globally is wasted, [1] the boost in food production would create an even harder burden on global Carbon discharges [1]. These difficulties, joint, place food damage as a key problem that effects worldwide discharges, roots waste of resources and restricts the adequate fulfillment of nutritional needs of populations and if left unresolved, food loss will continue to amplify with population growth and increase in demand on food production and supply systems.

All of this leaves a vacuum for an industrial shift towards energy efficient, sustainable methods of food preservation that can generate decent quality of preserved food items that is coherent with global food requirements and consumers' criteria [1]. To conclude, there is a need for food preservation methodologies and systems which would fit the following criteria:

1. Low CO_2 emissions [1]
2. Low capital cost [22]
3. Low energy application [26]
4. Maximum load on free energy
5. Significant worth of well-preserved food merchandise [3]. Consistency of produce with buyer demands [1].

Methods of food preservation

To prevent post-harvest agricultural produce from going to waste, different methods are employed. These methods include dehydration, thermal treatment [4] [5], radiation treatment [6]pickling, freezing [7], Ozone treatment [8], pasteurizing, storage in dehumidified environments [27] [28] and more. More recently, nanotechnology has gained quite some interest for its applications in food preservation due to its potentially high energy efficiency [9].

A strong case can be made for preserving post-harvest crops in the form of dried fruit and vegetable snacks. Given that many drying methodologies can be shifted to solar heating or its derivatives such as solar-regenerated desiccant dehumidification or heat-based cooling systems like vapor absorption cycle, our focus is directed towards moving energy consumption of food drying process towards renewable solar heat as much as possible and reduce the reliance of the drying process on energy intensive, eco-hazardous methods. Our next most important objective is to increase the aesthetic and appetizing kind of dried fruit or vegetable appetizers, creating them fit to compete with relatively unhealthy snacks in order to provide a valuable and healthy alternative to consumers. Both goals tie in with our third goal of reducing the overall cost of production of these snacks to produce food items that are affordable for low-income population. Combined, these three goals should result in a product that is sustainable, affordable, and healthy – hitting different criteria in the market and producing a high quality exportable Pakistani product.

The problem that we need to solve has been defined and we now have a clear direction for the literature review which is the process of data gathering and analysis.

Figure 2

CHAPTER 2: LITERATURE REVIEW

History and significance of food dehydration:

The drying of food objects is an antique process of conserving nutrients and energy. It is even older than cooking or pickling [1]. Drying food items allows them to be stored for several years which used to be vital in ancient times when humans used to seasonally hibernate like other animals and domestic agriculture was not commonplace. Even after the agricultural revolution of ancient Egypt, dehydration of food items remained a major method of food preservation due to the uncertainty around harvesting yield.

In modern times, however, agricultural harvesting is not much of a global or even local threat. But food dehydration remains to be implemented worldwide. It is utilized to get dehydrated fruit foods and to decrease the water mass in a delivery of fruit, making it viable, energy-economical, and more affordable to carry food crops.

Different drying technologies:

Different methodologies have been used domestically, commercially, and industrially to dry food items each offering different perks and limitations. Here is a quick review of these methodologies:

Open sun drying:

The most common method of dehydrating food is simply leaving it out in the sun for a few days with some sort of net to protect it against birds and insects. According to [2], this method is the most common in places like East Africa because it requires little to no capital investment and has no operational energy requirement whereas other, more efficient, and effective methods have the adoption barrier of capital investment and availability of cheap energy.

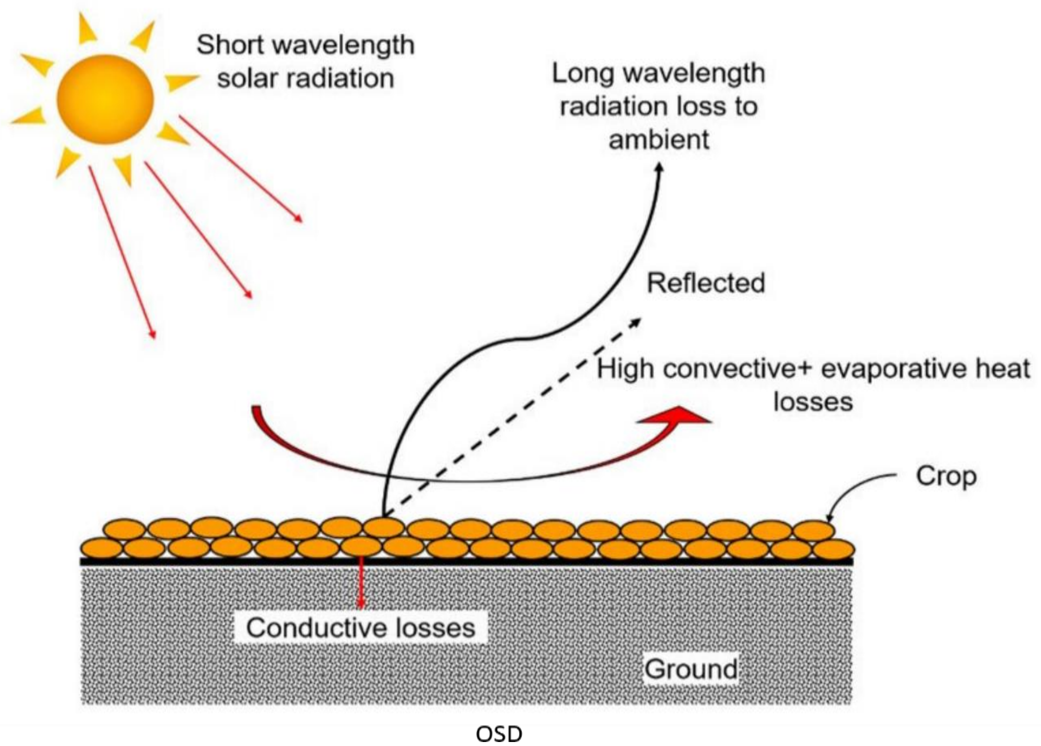

Figure 3 Open Sun Drying

Convective drying:

The name indicates, convection drying works by letting hot air to give over the food item to be dehydrated, transferring heat to the food which removes moisture from it [3].

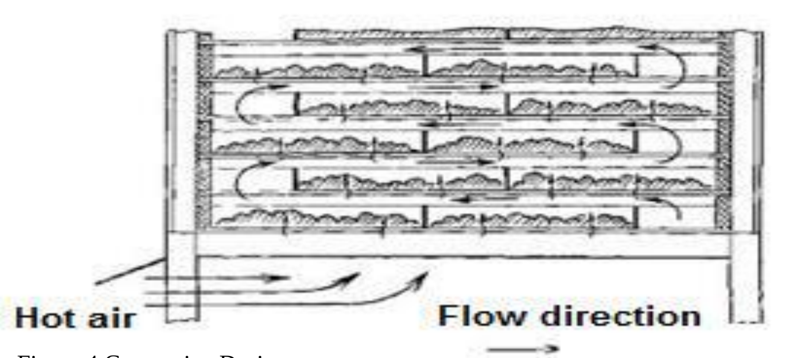

Figure 4 Convective Drying

Convection drying can be done by serpentine flow through trays or by parallel, cross, or counter-flow over plates as depicted in the figures.

Morales et al. [4] did an investigational drying of strawberries using convection with hot air varying from temperatures 60 – 90 deg-C and it was discovered that the maximum product quality was obtained in the range of 70 – 90 deg-C suggesting that higher temperature is more suited for food drying.

Figure 5 Convective Drying

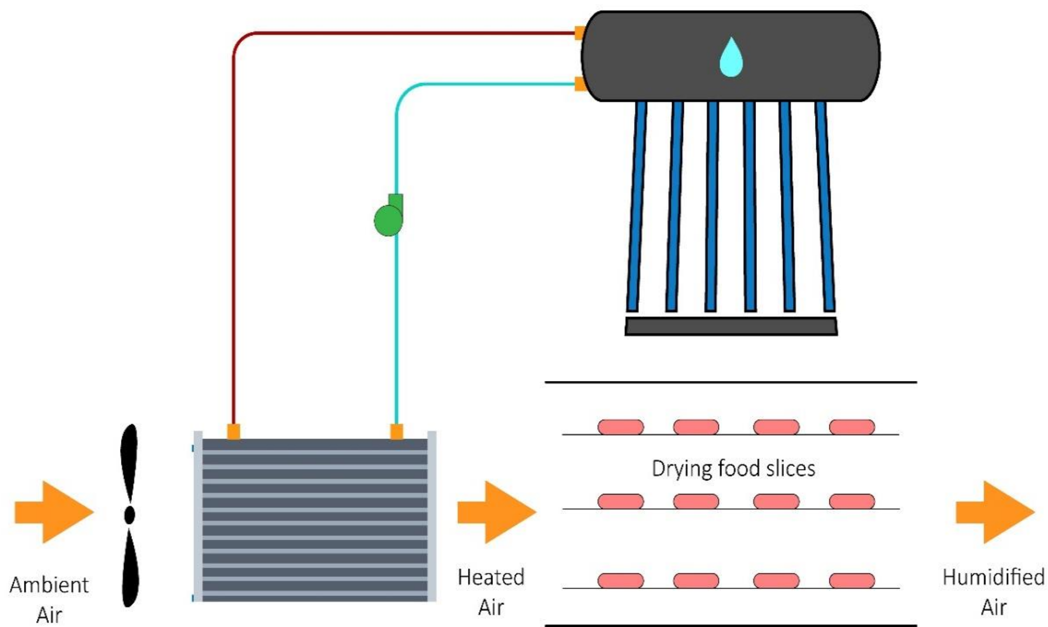

Figure 6 Convective Drying by Heat Exchanger

[5] used convection-drying to dehydrate sweet potatoes and found the method to be second only to freeze-drying in terms of moisture removal from the food product. Though, the research did not carry out any trials using radiation methods.

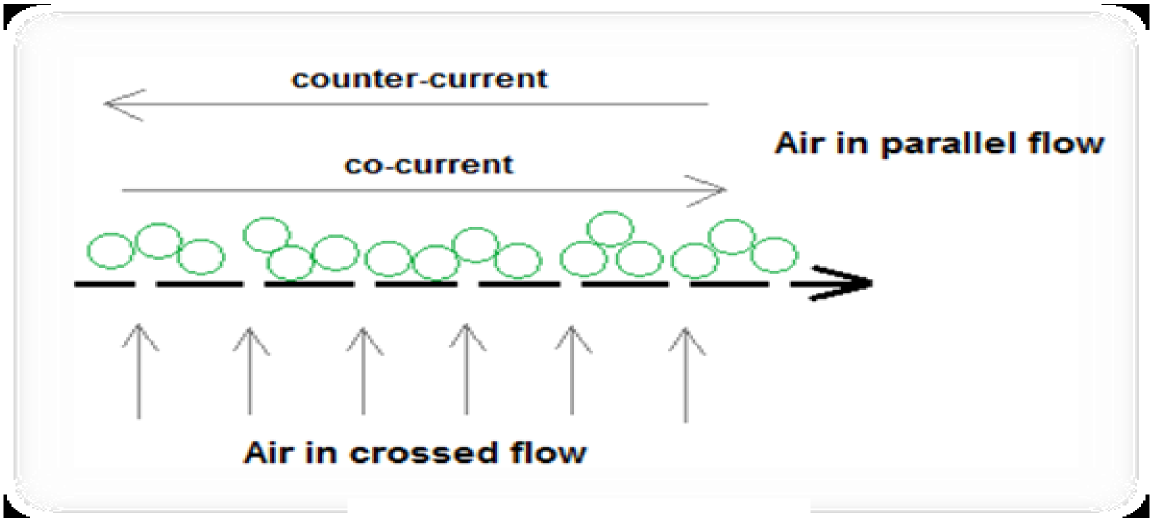

Figure 7 Air Flow

Microwave Drying:

Microwave radiation is electromagnetic radiation ranging in the frequency range of 300 MHZ – 300,000 MHZ with a wavelength between 1 mm and 1 m. Microwave radiation can dry food with lower time and energy consumption. [6]. It is since radiation methods such as MW drying penetrate the food item and heat it volumetrically as opposed to only heating the surface and allowing the heat to conduct through the rest of the food item's volume like convection drying. An added benefit of MW drying is its ability to be combined with other drying methods [7].

Ultrasonic Drying:

Ultrasonic treatment can be used in the dehydration process to increase the rate of mass transfer and overcome these difficulties. At the similar moment, the rehydration assets of the dried foods can be enhanced by means of using ultrasonic waves to create microscopic channels, which may make moisture removal and gain easier. The remedy has been utilized to achieve superior drying rates at the equivalent temperatures or sufficient drying rates at decreased temperatures. In overall, this one has been treated as several procedures, such as ultrasound-aided convective dehydration, ultrasound-aided osmotic dehydration, ultrasound-supported vacuum dehydration, and ultrasound-backed freeze dehydration. The ultrasound has been used together with a dehydration procedure or as pre-treatment in the methods as direct or indirect contact. In addition, other applications- and apparatus-based ultrasound treatments have been enhanced throughout the dehydration procedure to enrich food quality [8].

Infrared Drying:

Infrared drying (IR drying) is considered a promising drying method for food products. When infrared radiation is used to dry food products of high moisture, the energy is penetrated the materials to a small depth and then is converted to heat. Compared to conventional drying knowledge, this drying technology has the benefits of superior energy productivity, even heating up of items, easy control of material temperature, good quality of the final products, and low energy costs. Several more benefits of IR heating are modifiability, flexibility, ease of the equipment, easy mixture with other heating methods such as convective, vacuum, and microwave heating, inexpensive and uncomplicated installation, and use. [9] conducted an experimental investigation on the freeze-drying and infrared-freeze drying of Cordyceps militaries. The results showed that infrared-freeze drying could reduce up to 17.78% of the drying time and up to 18.37% of the energy consumption at the same drying temperature compared to freeze-drying. The quality of final products under infrared-freeze drying was as good as that under freeze-drying. [10]

compared the hot air drying and infrared drying characteristics of banana slices. They found that the drying time could be reduced significantly by using infrared drying and the drying quality could be well preserved when the product temperature was kept at 70 °C or below.

Freeze Drying:

Freeze-drying is a system wherein water is sublimated with the aid of using the direct transition of water from solid (ice) to vapor, therefore omitting the liquid state, after which desorbing water from the "dry" layer[11] t is extensively used for the stabilization of tremendous meals, organic materials, and pharmaceuticals, consisting of proteins, vaccines, bacteria, and mammal cells. In the system, the first-class of the dried product (organic, dietary, and organoleptic properties) is retained [12]. Freeze-drying is a mass change system that calls for warmness transport. The warmness of sublimation is 2885 kJ/kg [13]. If too little warmness is furnished, the system may be slow, in an effort to boom its costs. If the furnished warmness flux is simply too excessive, it'll motive an accumulation of warmth withinside the fabric and an boom in its temperature, therefore main to the opportunity of the arrival of liquid water. Hence, it's far extraordinarily critical

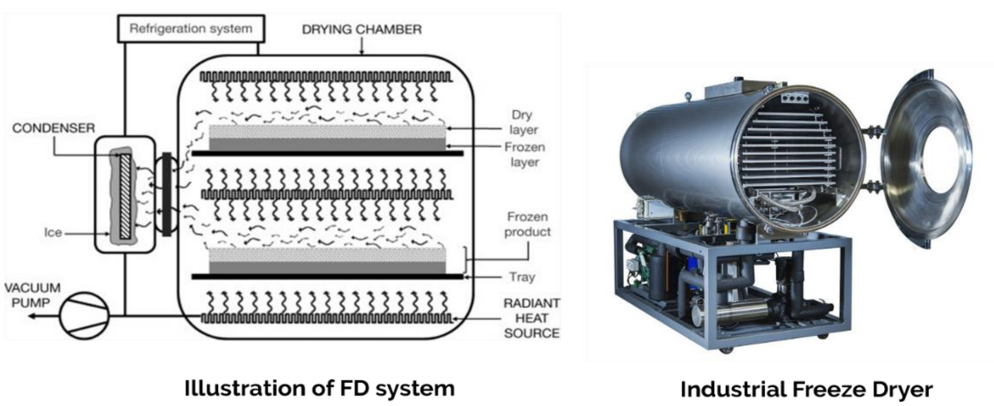

Figure 8 Industrial Freeze Dryer

to keep a stability among the quantity of warmth furnished and used.

Vacuum Drying:

Vacuum drying (VD) has a few extraordinary traits consisting of a better drying rate, decrease drying temperature, and oxygen-poor processing environment. These capabilities are useful and assist to enhance the first-class and dietary price of the dried culmination and greens consequently VD has been used to dry numerous culmination/greens [14]. Vacuum drying is conceptually the right technique for drying thermal and/or oxygen-touchy materials (consisting of culmination and greens) because of the benefit of getting rid of moisture at low temperatures and minimizing the opportunity of oxidation reactions. The drying kinetics and drying performance of vacuum drying for culmination and greens may be progressed with the aid of using combining microwave electricity to hoover drying.

Table 1 indicates a assessment of various drying strategies as mentioned above in tabular shape which permits us to summarize those strategies.

Dehumidification

Exposure of food to excessive temperatures over lengthy periods substantially damages meals first-class [23], that's why US pre-remedy and water blanching are used to lower drying time with out over-heating the meals all through the drying system. This is likewise the motive why techniques like Freeze Drying are advanced in phrases of meals first-class acquired. To reap higher first-class of dried meals items, excessive vapor stress variations are acquired with out over-heating the meals. CD and MWD normally acquire vapor stress distinction with the aid of using heating up the meals floor and growing the vapor stress of the moisture stress withinside the meals as compared to the air surrounding it. The identical stage of vapor stress distinction may be performed with the aid of using losing the vapor stress of the encircling air even as retaining the meals object at a slight temperature. Vapor stress without delay relies upon on temperature so the truthful manner of doing so might be to chill the air, however that comes on the value of massive strength losses. This is due to the fact the machine might try and acquire equilibrium and with a view to achieve this, the meals object will calm down with the aid of using convection with out inflicting lots moisture switch. Along with temperature, vapor stress additionally relies upon without delay at the Relative Humidity (RH) of a gas, implying that every other manner of losing the vapor stress of air might be to dehumidify it. [17].

Unlike cooling of air, while the machine attempts to acquire equilibrium while a wet meals object is surrounded with the aid of using dry air, it could most effective achieve this with the aid of using accelerating the mass switch from meals to air, re-humidifying the air. [17], exploration of its mixture with techniques consisting of CD, MWD and blanching pre-remedies is restrained in literature. Therefore, we're inquisitive about exploring the possibility of mixture of dehumidification with CD and MWD simultaneously.

The key findings of the literature review that will be used to develop our hypothesis can be summarized as follows:

Table 1. Table 1 Literature Review Summary

Finding	**Reference**
Shorter drying times are preferable for drying methods based on heating	[17]
High temperatures are damaging to food quality	[18]

Temperatures get elevated towards the end of thermal drying processes	[19]
Drying methods operating at low temperatures produce superior quality	[20]
Drying in dehumidified environments increases drying rate at low temperatures	[17]
Micro-needling increases drying rate and quality of end-product	[21]
Thinner food slices have a faster drying rate and quality compared to thicker slices	[22]
Thermal pre-treatment and starch removal shortens drying time and improves the quality of end-product	[23]

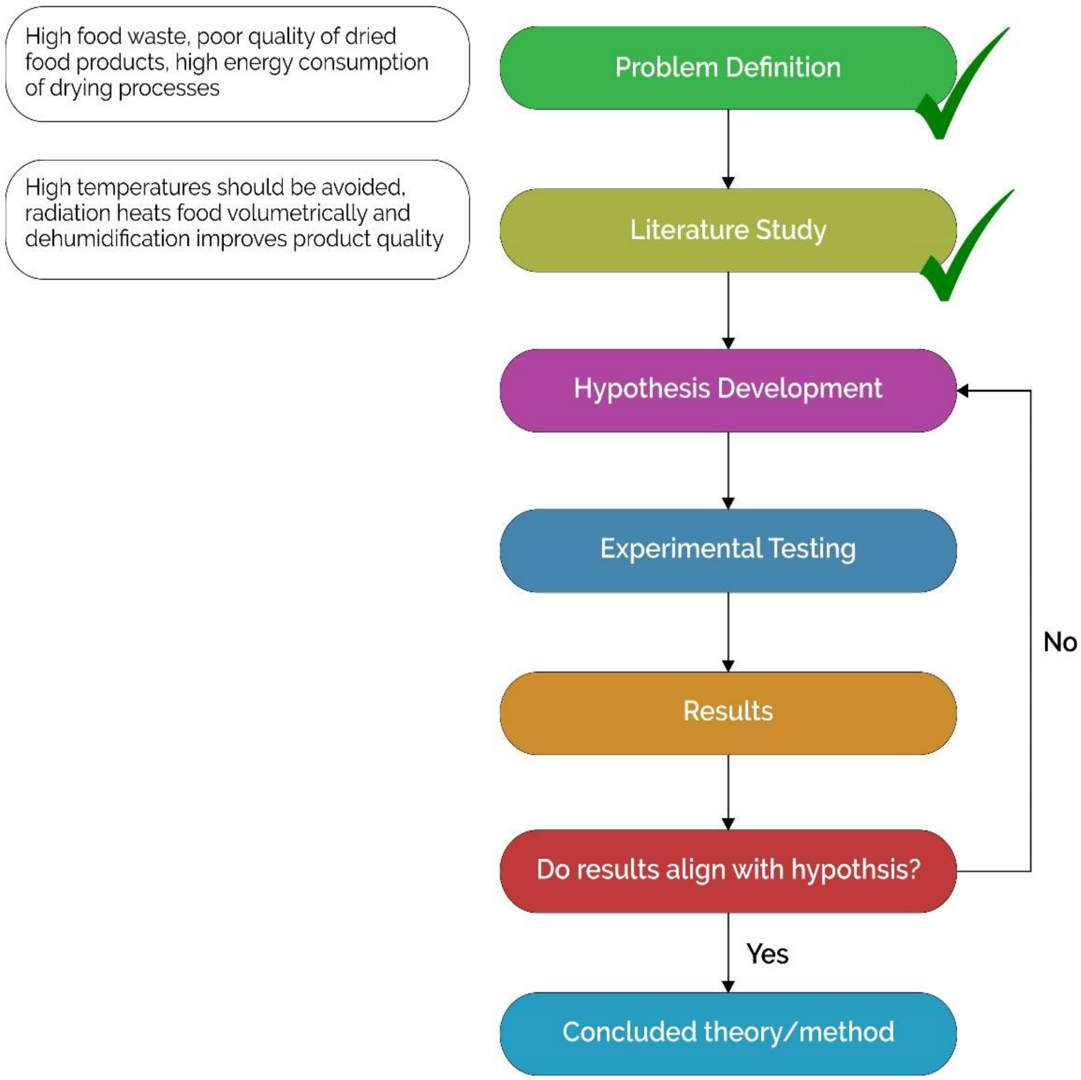

Figure 9 Literature Review Completed

Having studied the literature and generated data from experimental observations made by researchers over the last few decades, we now understand key data points that can be used to design a system that optimizes and improves our required parameters.

CHAPTER 3: METHODOLOGY

Design philosophy:

Simply put, the design philosophy behind this project is a fundamental application of the Fick's Second Law of Diffusion:

$$\frac{\partial \Psi}{\partial t} = D\frac{\partial^2 \Psi}{\partial x^2}$$

Where,

D = Diffusivity

Ψ = Concentration

x = position

t = time

In the view of food drying, the rate of drying process is directly proportional to the difference in vapor pressure between the water molecules within the food item and surrounding ambient air. As the air absorbs moisture, its vapor pressure rises, and the drying process stops as soon as it equates to the vapor pressure of the remaining moisture within the food. Thus, the driving force for our principle process is the vapor pressure difference.

Microwave drying works by increasing the vapor pressure difference of the moisture, helping the evaporation process faster. Convective drying has same mechanism. But another mechanism to accelerate drying would be to reduce the moisture already available in the air surrounding the food item. This increases the threshold or capacity of maximum moisture that air can hold before it must be exhausted and increase in vapor pressure difference as well.

Thus, we are adding to the academic and industrial literature by complementing Microwave and Convective food drying with desiccant drying of the air.

Design schematic:

In the 1st step, the system starts with a highly concentrated desiccant solution at room temperature that remove water content the air. The desiccant is diluted in the process by absorbing moisture from the air and is regenerated by concentrated solar heat. The dehumidified air is optionally heated by concentrated solar heat in the 2nd step This step is optional because we are exploring salt-based desiccants that release heat upon absorbing moisture, the heating of air because of advection with the liquid desiccant solution may be enough to remove the need for additional convective heating.

In the 3rd step, the dehumidified air surrounds the food item that is acted upon by Microwave radiation as well. The compound convection-MW effect dries the food item rapidly. The air is exhausted continuously or sequentially.

The concept design is shown in figure 3 below:

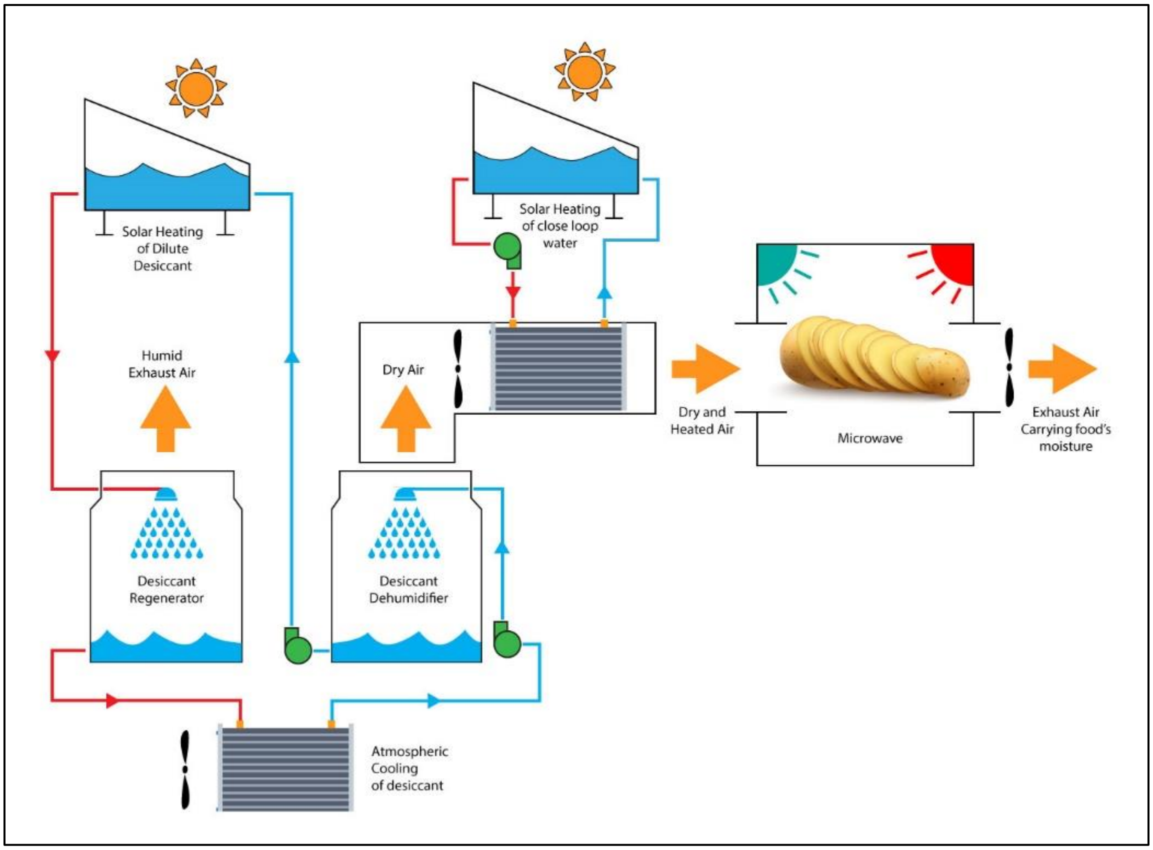

Figure 10 Concept Design

Design Calculations:

Dehumidification algorithm:

The dehumidification algorithm is based on the application of Fick's law. We iteratively change a small step amount of moisture in both mediums that are in contact with each other. With air and desiccant solution, the vapor pressure difference tells us whether moisture will move from air to the desiccant solution or vice versa. If a positive vapor pressure gradient exists, it indicates dehumidification of air and moisture will move from air to the liquid solution. Once this gradient is eliminated, the desiccant solution will not be able to dehumidify any more air and will have to be heated and regenerated. The resultant air will be dry and fit for removing moisture from food items. After heating the desiccant, the vapor pressure gradient becomes negative showing regeneration of desiccant as moisture is removed from it then removed via the exhaust. The resulting MATLAB program made with this algorithm matches the experimental results from the literature [15].

Food drying algorithm:

The algorithm for calculating the interaction between food being heated by a Microwave while surrounded by dehumidified air is very similar to the algorithm used for the interaction between liquid desiccant solution and ambient air. This is because both types

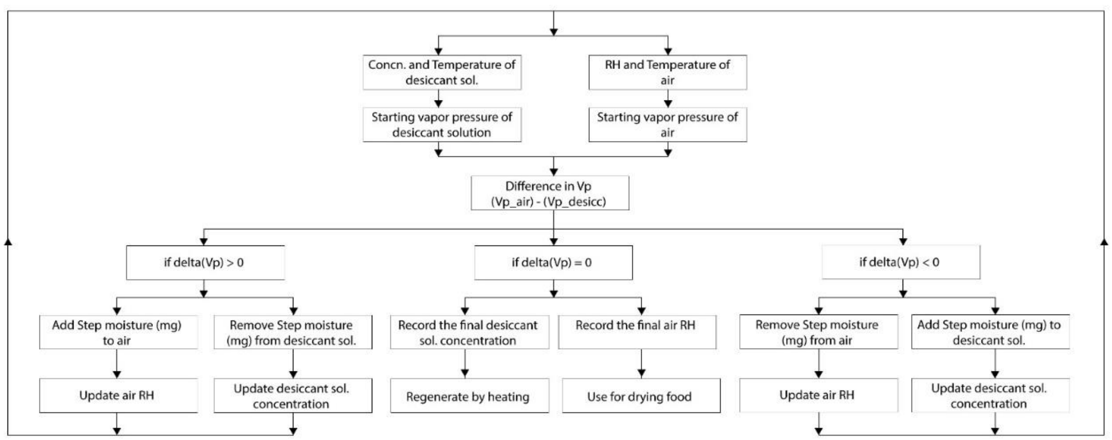

Figure 11 Dehumidification Algorithm

of interactions hinge on vapor pressure difference as the driving mechanism of moisture transfer between the media. However, it must be noted that in this algorithm, the possibility for dvp < 0 is not entertained. This is because as soon as vapor pressure equilibrium is achieved, the air is exhausted and replaced by a fresh charge of dehumidified air and unlike desiccant solution that needs to be regenerated, the air in this case does not have any need for regeneration or re-drying since it is a naturally renewable resource regenerated by the vapor cycle by weather changes.

Energy consumption algorithm:

The calculation for total energy consumed, the amount of airflow rate required, and the time taken to dry any amount of food is quite simple. The energy consumption can be found by simply using the fact that to remove 1 g of water from the food item, 2.2 kJ of energy is needed theoretically as it is the heat of hydration for water. Thus, any rate of food dehydration can be gauged against any energy consumption rate or power which would in turn also give us the time taken for any amount of dehydration.

In summary, our hypothesis is that thermally blanching micro-needled thin food slices as a pretreatment should be the most beneficial pre-treatment. In the constant rate drying period, we should be heating the food volumetrically with MW as well as evaporating surface moisture with high-temperature CD. After the critical moisture has been achieved and the falling rate period starts, our system should gradually start reducing the temperature of the air in contact with the food surface as well as dehumidifying it. We believe that, based on the data from the literature, this combined hybrid method would result in the finest optimization between dried food quality, energy consumption, and drying rate. You can see in Figure 9 that the methodology is defined at this point.

ANSYS Modeling:

A CFD model was developed on ANSYS fluent to study and validate that the drying of any bulk food item is non-uniform, and the drying rate drops as the observation probe moves downstream. To account for this problem, we used a turbulent air inflow pattern so as to obtain a more uniform surface drying rate.

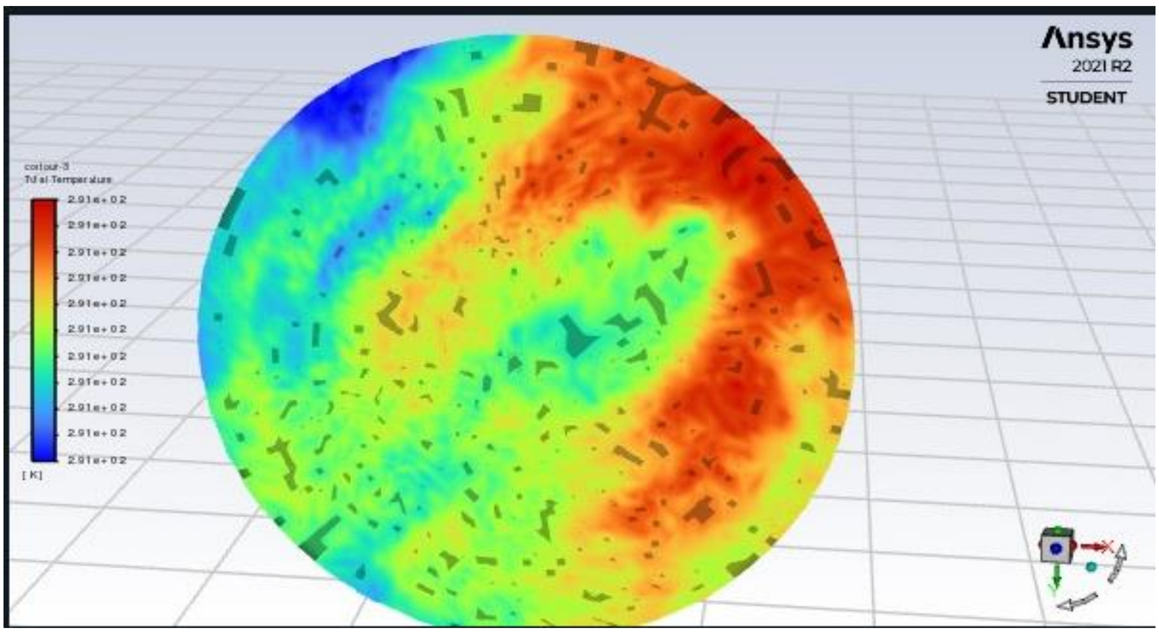

Figure 12 ANSYS Modeling

MATLAB Mathematical Modeling:

The mathematical model was also developed on MATLAB and curve-fitted to experiments. The mathematical model uses a simple CFD model of 2^{nd} Fick's law of mass transfer with an error correction term to account for drop in mass transfer rate over time.

```
m_initial = 1;                          %kg
x_initial = 90;                         % water/dry mass
x_final = 50;                           % water/dry mass
dry_bulb = 60;
RH = 5;
food_temp = 25;
Y_a = 0.0062;
Y_s = 0.0201;

m_dry_initial                = m_initial*(100-x_initial)/100;
m_water_initial              = m_initial - m_dry_initial;
m_dried_product              = m_dry_initial*(100/(100-x_final));
water_removed                = m_initial - m_dried_product;
m_water_dried_product        = m_water_initial - water_removed;
m_dry_mass_dried_product     = m_dried_product - m_water_dried_product;

Xo = (x_initial)/(100-x_initial);
Xf = (x_final)/(100-x_final);
%Lewis' relationship: kg' = h/1000 - https://nzifst.org.nz/resources/unitope
kg = 0.015;
A = 0.0038465*300;
moisture_removal_rate = kg * A * (Y_s-Y_a);              %kg/s
water_to_remove = m_dry_initial*(Xo-Xf);                 %kg

latent_heat = 2400;
energy_supply = latent_heat*moisture_removal_rate;       %kW

t1 = water_to_remove/moisture_removal_rate;               %s
t1 = t1/3600;
disp(t1);


f=0.85;          del_X = 0.001;       del_f = 0.001;
Xi=0.5;
Xf = Xi - del_X;
t=0;
while (Xi > 0.1)
        f = f - del_f;
        Xf = Xi - del_X;
        t = t+( m_dry_initial*(Xi-Xf)/(f*kg * A * (Y_s-Y_a) ) );
        disp([Xi, "", Xf, "", t]);
        Xi = Xf;

        %disp(t);
end
t=t/3600
```

Figure 13 MATLAB Code for calculation of various parameters

CHAPTER 4: EXPERIMENTATION

Material

R1G133-H045-01F 24V, 40-Watt centrifugal fan was used as the primary air flow driver for the experiments. The blower's airflow rate was controlled using a PWM voltage signal from BL Heli 32 ESC controlled by a STM32F411CEUx (black pill) controller with a KY-040 encoder. For convective heating, a Bfreeze 300 Liter, 30-tube evacuated tube Solar Water Heater was used. The desiccant was heated using a spiral wounded 2-meter copper coil of 5 mm inner diameter and 1 mm thickness. The desiccant was pumped using the SP100 submersible pump.

Methodology

We dried potato slices of 5 mm thickness, weighing 5 grams each using different drying combinations to study the net result. The experiments were done sequentially to develop an empirical proof of improving performance with each combination.

Experiments:

The experiments are designed to sequentially confirm the theoretical bases on which our system is designed. We first designed experiments to conduct CD at constant temperatures to confirm that high convection temperatures result in deterioration in product quality. We then confirmed that dropping the temperature

1. CD:

Potato slices were dried using convection heating at constant temperatures as well as variable temperatures. The slices were laid on a cooking steel grill in a duct and air at constant temperatures of 60 deg-C, and a flow rate of 1.5 m/s was blown over the surface to measure drying time. The mass flow rate of the air was known to be 0.040 kg/s. Using the mass flow rate, the temperature and humidity difference upstream and downstream of the food slices, and the weight of the food in the duct was measured after different time intervals, Specific Energy Consumption (SEZ), drying time, and final moisture content. Following this, the next round of experiments used variable temperatures, the temperature was raised from 40 deg-C to 80 deg-C over the two falling rate periods. In another experiment, the inverse was done as the temperature dropped from 80 deg-C to 40 deg-C over time. It was studied which configuration offers an improvement in drying time and which prevents surface scorching and coarse hardening.

2. MW+CD

In the second type of experiment, CD at constant temperatures of 40, 60, and 80 deg-C was combined with a constant 1000 Watt MW heater, and all determinant parameters were evaluated. In the next experiment, convection temperature was started at 80 deg-C and reduced over time.

3. MW+CD+DD

In the third type of experiment, Microwave heating was combined with convective heating with dehumidified air. The Effect of Relative Humidity on drying time, SEZ, and end quality of the dried product was studied. In the next variation of this experiment, variable convection temperature and variable humidity levels were used alongside MW radiation. Humidity was not artificially dropped during the constant rate drying period. In the falling rate period, humidity and temperature both dropped over time. This is the configuration of the solution that is supposed to deliver the most optimal results.

This is the summary of each experiment and the predicted theories that the experiments are designed to test:

Tested parameters: SE (SPECIFIC ENERGY), Drying rate, drying time, and product quality.

Table 2 Tested Parameters

Experiment	**Expected results**
Constant Temperature CD	• Higher drying rate at high temperatures • Better product quality at high temperatures
MWD+constant temperature CD	• Higher drying rate than constant temperature CD • Better product quality than constant temperature CD
MWD+constant temperature CD+constant DD	• Higher drying rate than what's obtained without dehumidification • Poorer product quality than what's obtained without dehumidification

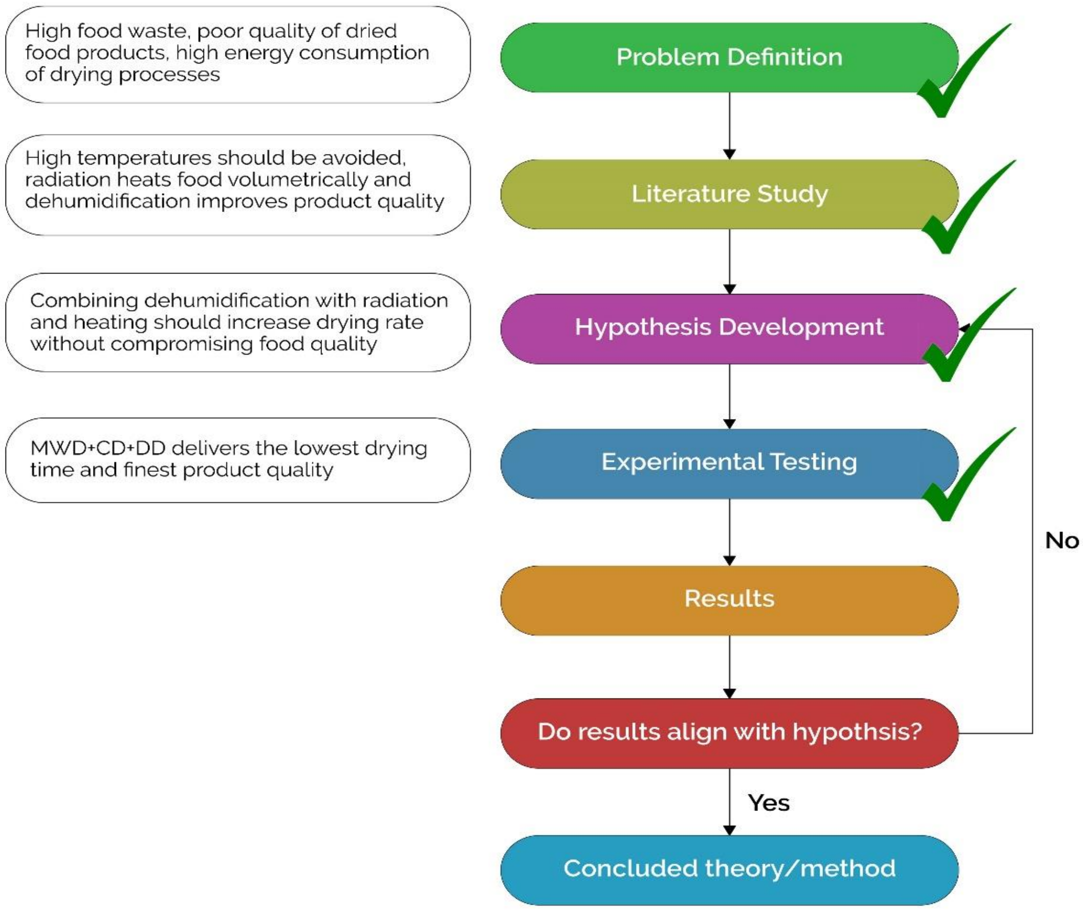

Figure 15 Experimentation Completed

CHAPTER 5: RESULTS AND DISCUSSIONS

This section of the report discusses the experimental procedures we used for microwave convective drying. The main components of an MCD drying test facility are:

1. Variable power microwave generator (magnetron),
2. Waveguide,
3. Microwave cavity
4. A Solar Water Heater for hot air supply with a fin-tube

Microwave generators can be a variety of devices such as magnetrons, klystrons, power grid tubes, traveling wave tubes, and gyrotrons, but the most used source is the magnetron, which is more efficient, reliable, and available at a lower cost than other sources (National Research Council 1994). Microwave generated in magnetron is guided through waveguides to the cavity where the materials are placed. At the same time, hot air needs to be supplied to the cavity to combine with convective drying.

Experimental results:

The system was developed by placing food slices on a grill inside a Microwave own modified to allow for air inlet and outlet. In the first experiments, the Microwave was kept off while hot air of 60 deg-C was blown over the food slices. Hot air was produced by running hot water through a fin-tube heat exchanger with a centrifugal blower. The hot water's flow rate was controlled to adjust the air temperature at Microwave inlet. We used a bypass valve upstream of the centrifugal pump to control water flow rate. A gas thermometer and hygrometer was used at inlet and another at outlet to measure air temperature and humidity over time. An anemometer was used to identify air flow speed and the fan was adjusted to supply the desired air flow at 1.5 m/s.

In the second experiment, Microwave was turned on at constant power and the same instrumentation was used to take measurements.

In the third experiment, a desiccant dehumidifier is installed upstream of the hot air flow system. This dehumidifies the input air before it is heated and enters the Microwave oven. The dehumidifier is constructed using a small liquid showering system. A 50% w/w CaCl2/Water solution is sprayed in the cooling tower which interacts with incoming air in a cross-flow setting. While LiCl and LiBr are superior salts for dehumidification compared to CaCl2, CaCl2 was used because of its non-toxic nature. The system drops the RH of ambient air from 50% to 20% which after heating in the fin-tube Heat Exchanger, drops down to 10%. This heated and dehumidified air enters the Microwave oven at the same speed as the other experiments i.e. 1.5 m/s.

The table 2 below shows the experimental readings

Table 3Experimental Values of Air velocity and RH

Exp	**Air Temperature (ºC)**			**Air RH (%)**			**Weight (g)**		**Drying Time (min)**	**Specific Energy (kJ/kg)**	**Scorching level (L/M/H)**
	Ambient	**Inlet**	**Outlet**	**Ambient**	**Inlet**	**Outlet**	**Initial**	**Final**			
1	36	59	51	43	16	23	100	17	35	4.8	HIGH
2	37	58	56	43	17	28	100	17	12	3.6	MEDIUM
3	35	60	53	42	6	19	100	16	22	3.9	LOW

Discussion:

Temperature and moisture are the two main parameters that need to be measured accurately during the drying process. The efficacy of an experimental setup depends on how accurately these two parameters can be measured. Additionally, the air velocity distribution plays an important role in the drying rate because it affects the heat and mass transfer coefficient which is essential for modeling.

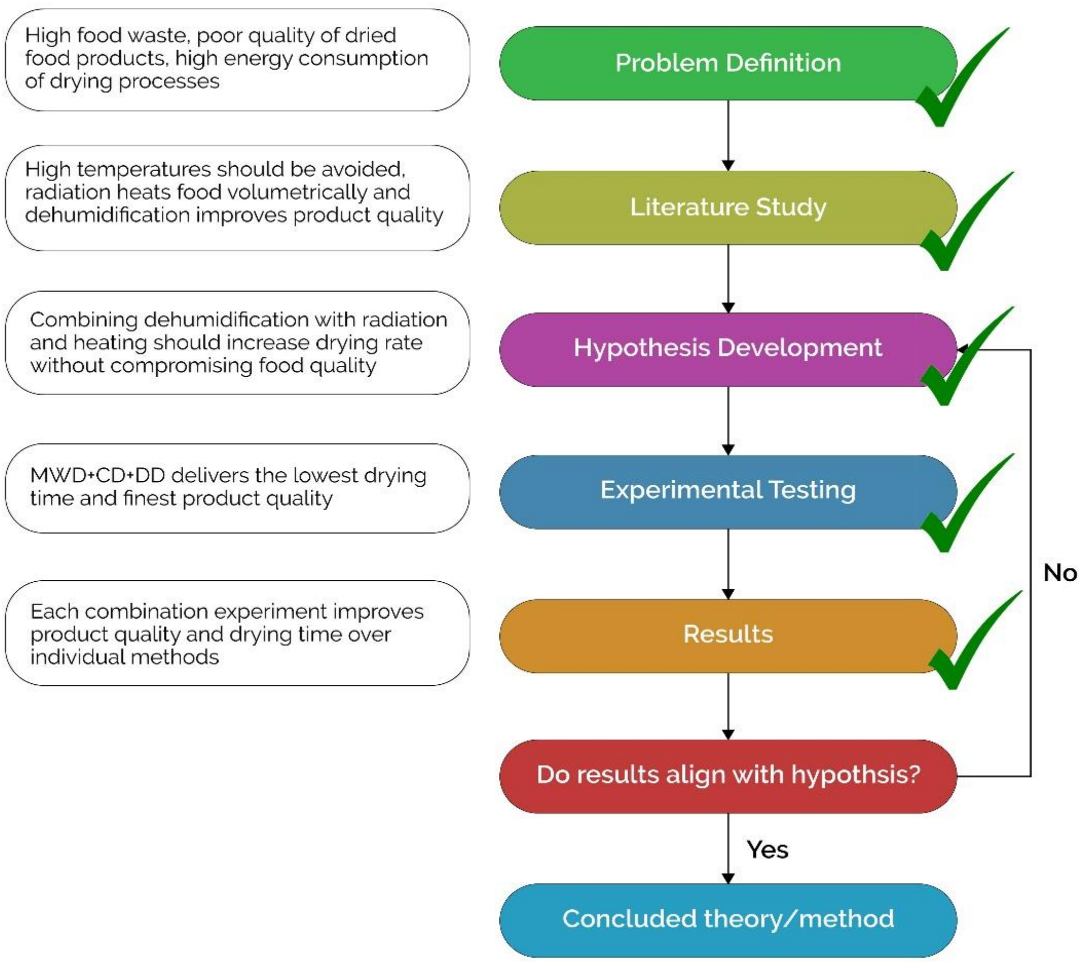

Figure 16 Results Achieved

CHAPTER 6: CONCLUSION AND RECOMMENDATION

The major challenge in microwave systems is the non-uniformity of electric fields. Future research should involve addressing this problem focusing on obtaining more uniform electric field distribution thus obtaining uniform temperature and moisture distribution. One potential solution could be using multiple magnetrons at appropriate locations in the chamber. Mathematical modeling and simulation would be essential to doing such investigations. The plant-based food materials are hygroscopic in nature, containing free water and bound water. The transport mechanisms of free water and bound water are different. Therefore, the future modeling study of MCD should include a separate mechanism for the transport of free and bound water. Moreover, the models should be able to predict the effect of process parameters on drying kinetics, then the models can be used to optimize the process and suggest an appropriate strategy for applying MCD to avoid overheating and gaining maximum food quality with minimum energy usage.

Conclusion:

This report provides an overview of the MCD process which focuses on drying techniques, experimental results and mathematical modeling. Moreover, the comparative study of drying time between microwave-assisted drying and convective drying for different materials is calculated and discussed. It clearly shows that drying time can be saved up to 90% by applying the microwave technique. Considering this huge drying time saving of MCD, there is enormous potential for this process in industrial applications. The critical review of experimental facilities showed that the experimental facilities should be equipped with real-time moisture and temperature measurement of the sample and should have uniform airflow distribution. It was also categorically proven that dehumidifying the surrounding air around food items prior to heating and microwave application results in the best product quality and most optimal energy to output ratio. The risk and safety issues of creating a vent for airflow in a microwave cavity were investigated. Although the setup with a single-mode cavity can provide an understanding of physics, its performance is sensitive to product position and geometry. In contrast, multimode cavities are less sensitive to product position or geometry but provide uneven heating. However, this uneven heat can be minimized by applying microwave intermittently, providing turntable or model stirrers, and by suitable cavity design. Continuous microwave-convective drying may overheat and damage quality which can be overcome by intermittent microwave-convective drying by applying the appropriate power level and pulse ratio. The mathematical modeling can help to optimize the intermittency and power level of the microwave for better product quality and energy efficiency. One major disadvantage of microwave application is the non-uniform heating due to the standing wave pattern. A comprehensive multiphase mathematical model can also help in selecting magnetron size, position, and cavity shape to obtain a more uniform heating pattern. Therefore, future research should focus on scaling up and optimizing this technology for industrial applications.

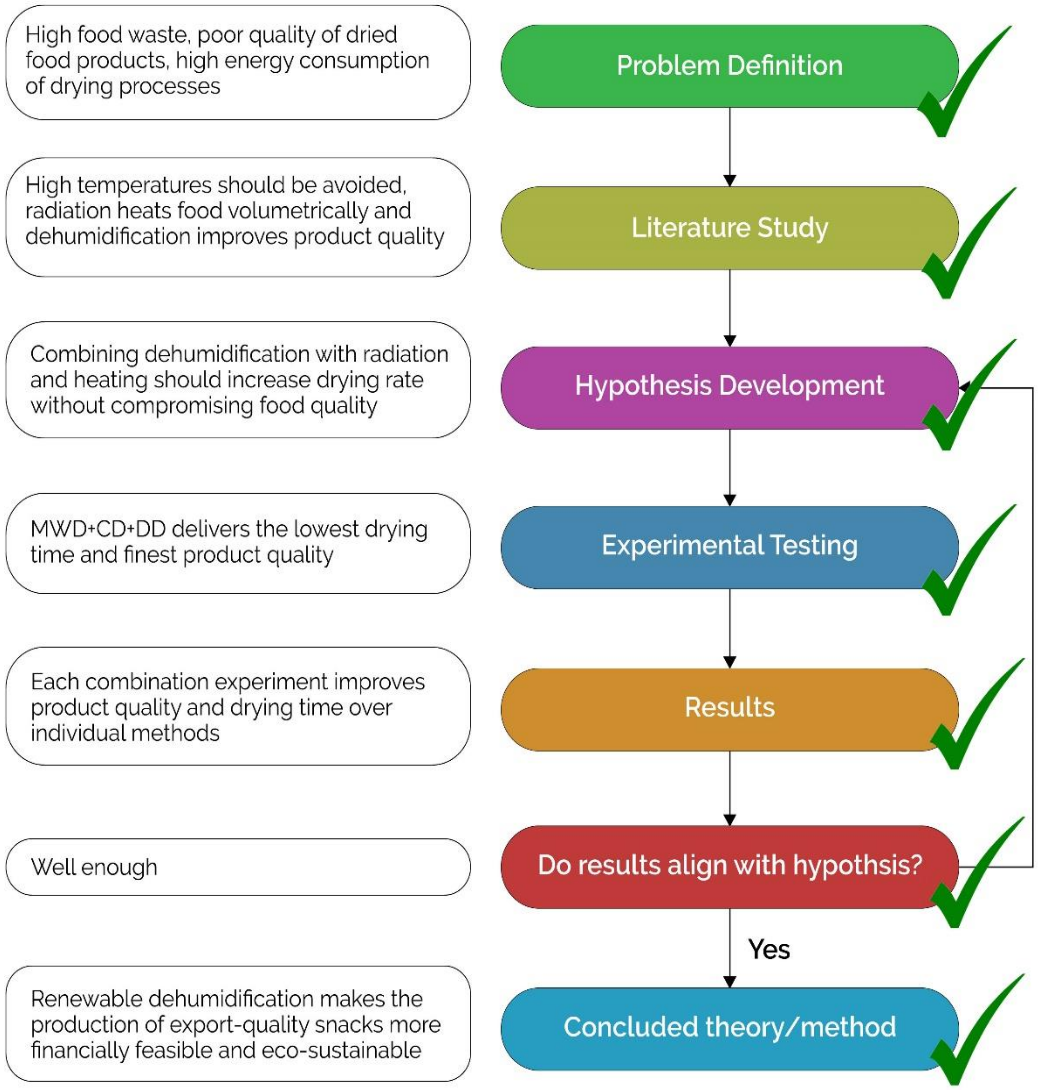

Figure 17 Confirmation of Hypothesis

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APPENDIX I: MEDIA

Following pictures are the CAD models and the actual components manufactured:

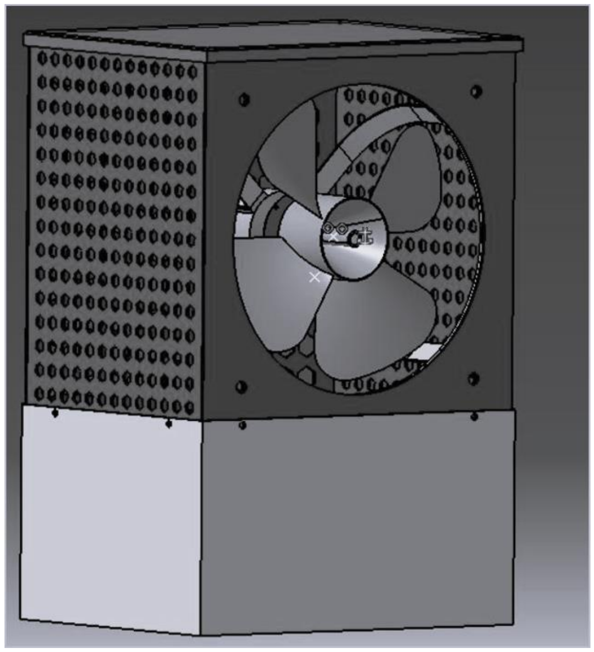

Figure 18 CAD model of Dehumidifying Chamber

Figure 19 Manufactured Dehumidifying Chamber

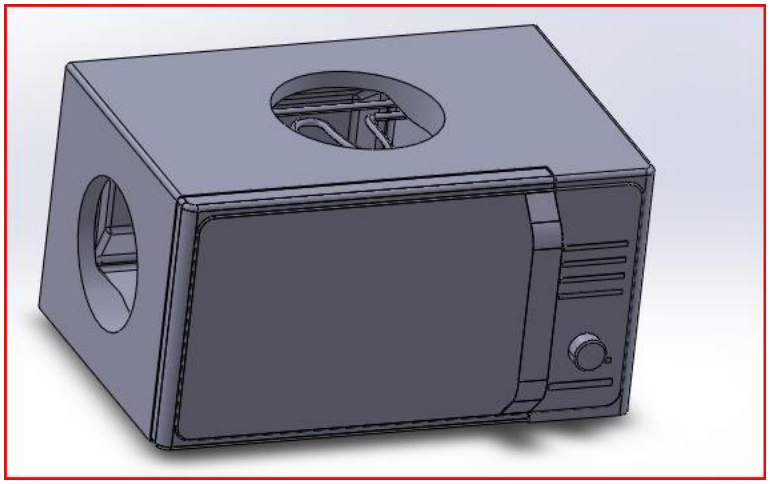

Figure 20 Drying Chamber

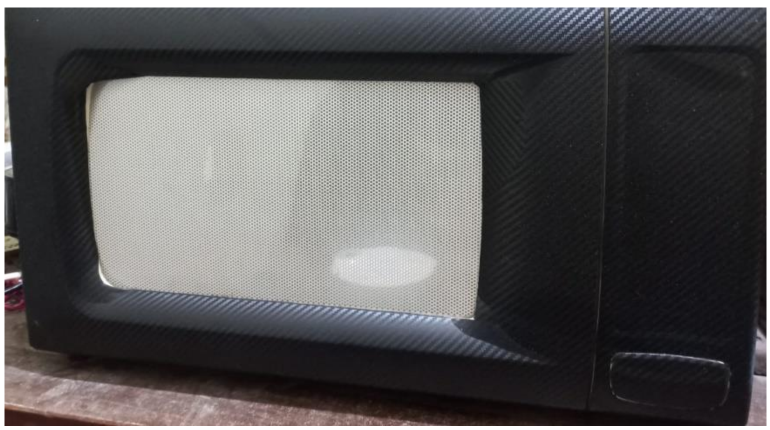

Figure 21 Drying Chamber Front View

Figure 22 Drying Chamber Top View