सौर संचालित हवा द्वारा इन्फ्लेटेड अनाज ड्रायर का विकास

DEVELOPMENT OF SOLAR POWERED AIR INFLATED GRAIN DRYER

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DEVELOPMENT OF SOLAR POWERED AIR INFLATED GRAIN DRYER

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By

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"Acknowledge all of your small victories and people who play a part in it. They will add up to something great."

"The best and safest thing to keep a balance in your life, acknowledge the great powers around us and in us. So, it is essential that I acknowledge the great powers, who paved the way on which I have walked so far. Any accomplishment requires the effect of many people along with the sincere guidance of experienced persons and blessings of **Almighty**".

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List of Abbreviations

ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
BCR	Benefit cost ratio
db	Dry basis
df	Degrees of Freedom
FAO	Food and agricultural organization
HRY	Head rice yield
IARI	Indian Agricultural Research Institute
IRRI	International rice research institute
LCD	Liquid crystal display
LSD	Latin square Design content
MRY	Milling rice yield
MHz	Mega Hertz
PB	Pusa Basmati
PV	Photovoltaic
RH	Relative humidity
RTC	Real time clock
w.b	Wet basis
GDP	Gross Domestic Product
FPC	Flat plate collector

Chapter 1

INTRODUCTION

Agriculture contributes 17% in India's GDP (Ministry of statistics and program implementation, Planning commission, Government of India, 2017) and provides food for more than 1.2 billion people generating a total employment to about 54.6% of the population. India holds the second-largest agricultural land (179.9 million hectares) in the world and food grain production covers the dominant part of the cropped area (65%) in Indian agriculture. India is the world's largest producer of millets and second largest producer of wheat, rice, and pulses. (Khatkar *et al*., 2016) India is the second-largest producer and consumer of rice in the world with production 105.48 million tonnes in 2014-15. Total production of wheat and coarse cereals during 2014-15 was 86.52 and 42.86 million tons respectively (Annual Report, Ministry of Agriculture and Farmers' welfare, Govt. of India, 2016-17).

Large amount of the grain produced is lost as post-harvest losses due to inappropriate handling and practices after harvesting. One-third of the food produced (1.3 billion tonnes), is lost globally during postharvest operations every year (Gustavsson *et al.,* 2011). The post-harvest losses in two major food grains, i.e. rice and wheat are about 75 per cent of the total post- harvest losses occurring at the farm level and about 25 per cent at the market level. In India the total post-harvest losses in cereals and pulses ranges from 3.87-5.96% and 4.28-6.06%, respectively. In paddy the post-harvest losses were 5.19 per cent. (Nanda *et al*., 2012)

Grains are generally harvested at higher moisture content in order to avoid shattering losses during harvesting for example rice is harvested at about 22 % moisture. High moisture level during storage can lead to grain discoloration, encourage development of moulds, and increase the likelihood of attack from pests. It can also decrease the germination rate of the seed. Drying of the grain facilitates the farmers to wait for higher price of commodity and regulate demand supply chain. Thus, it becomes crucial to dry the grain as soon as possible after harvesting. Ideally, the harvested grain should be dried to safe level of moisture content within 24 hours. Delays in drying, incomplete drying or ineffective drying may reduce grain quality and ultimately result in losses.

Ideally, the paddy needs to be dried on farm level immediately after harvest, mostly done through sun-drying, if the weather is favourable. For the production of better quality rice and the prevention of the weather risk farm level dryers can offer solutions.

Grain drying methods mainly include traditional and mechanical systems with varying technological complexity and capacities for either farm or commercial level. Traditional drying systems are still practiced in many areas because of its low cost and ease of management. Various traditional methods that are being widely used across the country are sun drying the grain on pavements, mats, nets etc. in case of cereal crops field drying and stacking are also common methods but lead to large amount of losses and shattering when grains are over dried.

Sun drying of grains although is cheapest among all the method and doesn't involve usage of any fuel but at the same time has certain major limitations. The product is susceptible to contamination due to dirt, insects and wastage by birds. In this process grain may be spoiled due to sudden and unpredicted rain. There is no control of temperature over crop drying which may lead to quality deterioration. While sun drying the grains, over drying may cause loss of germination power, nutritional changes, sometimes complete damage (Sontakke & Salve, 2015).

The commonly used mechanical dryers for drying of paddy are fixed batch bed dryers, recirculatory dryers and flash dryers. Fixed batch dryer are simple and affordable dryers generally kerosene or rice hull fired with capacity of 1-10 tons. These dryer are labour intensive and require large amount of fuel. Recirculatory dryers are automatic dryers requiring less floor area. Flash dryers are commonly used for quick drying of grains to 18% moisture content. These dryers are expensive in operation. Mechanical dryers addresses some of the limitations of natural sun drying and offers advantages such as reduction in handling losses, better control over the hot air temperature, and space utilization. However, they suffer with the limitations of high initial and maintenance cost, adequate size availability, and lack of knowledge to operate these dryers, especially with smallholders. Due to these limitations, these dryers are rarely used by smallholders in the developing countries. (Alavi et al., 2011)

India recieves high solar insolation providing a perfect opportunity for using sunlight based power in the country. Solar energy is the largest exploitable renewable resource as more energy from sunlight strikes earth in an hour than all of the energy consumed by humans in an entire year. This solar potential can be harnessed for drying of the grains in effective manner. The daily average solar energy incident over India fluctuates from 4 to 7 kWh/m^2 with around 1,500–2,000 daylight hours per year (depending upon location), which is significantly more than current total energy utilization. Innovative breakthroughs for cost-effective photovoltaic technology lately have made the solar energy of high utility (MNRE, 2013).

The use of solar dryers in the drying of grains can significantly reduce or eliminate product wastage, improve post-harvest handling at cheaper cost at the same time enhance productivity of the farmers towards better revenue derived. The quality of products dried in this way is excellent, due to the fact that the food is not in direct sunlight (cabinet or in-house dryer). The time consumed in solar drying is also comparatively lower compared to sun drying. (Sharma *et al*., 2009).Drying of grains in a solar dryer are mainly affected by ambient temperature, rate of radiation received by the solar collector, the relative humidity of air and the wind speed of air.

Inflatable solar air collectors also find potential application in drying of agricultural commodities. These work on the principle of solar dryers and can provide technical and financially viable solution for drying in energy deficit areas. Solar collectors used in agriculture can be classified as cylindrical or semi cylindrical plastic tunnels inflated by a constant flow of air and ventilated horticultural greenhouses. The inflatable solar collector develops a semi cylindrical format when air is injected in the confined space between the two covers walls (Koury *et al*., 2003).

Inflatable solar air heating collectors are compact, lightweight, inexpensive, self-supporting and self-erecting/storing. The performance of these collectors depends mainly on the air flow characteristics and geometry of the structure (Ruskis *et al.,* 2011).

Depending on the purpose of the drying cost calculation drying cost can either be stated as annual cost or as cost per unit of weight. If the assessment is done to compare the dryer with other drying systems, e.g. with sun drying, the cost per unit of weight is more appropriate. Case studies in Asian countries indicate that mechanical dryers with cost higher than 5% of the paddy value cannot be introduced successfully

(Phan Hien, 1998). Drying of paddy in artificial or mechanical dryer costs 5 to 8 times more than sun drying (Gummert, 2007).

Proper drying of the harvested crop is essential to maintain its quality and prevent its spoilage. Increasing cost of fuel and environmental damage are major reasons which promote usage of green energy. Mechanical dryers are expensive and lack in portability hence not suited for on farm drying of grains. The demand for low cost on-farm grain dryer which could effectively utilize the green energy available, can be manufactured locally and maintains the product quality after drying still prevails in the country and considering these specifics the present research work for developing solar powered air inflated grain dryer was undertaken with the following objectives:

1. Development of the solar powered air inflated grain dryer.
2. Performance evaluation of the developed dryer.

Chapter 2

REVIEW OF LITERATURE

Drying is the process that reduces grain moisture content to a safe level for storage. Harvesting of cereal grains is generally done at 20-23% moisture content. Drying is the most critical operation after harvesting the crop. Proper drying will maintain grain quality and minimize losses. Solar energy is an alternative and emerging source used for drying that can replace the conventional energy source. Air inflated solar collectors which have capability to generate sufficient heat by trapping the solar radiations and being used in drying process. This chapter deals with previous work done on grain dryers focusing largely on utilisation of solar energy and important parameters affecting the drying rate and performance of solar dryer.

2.1 Production and post-harvest losses in grains

World production of coarse grains in 2017 was 1381 million tonnes. Total food grain production in India in 2014-15 was 252 million tons. Rice and wheat are also major staple food for majority of population in the nation justifying their ever increasing demand. Rice and wheat production during 2014-15 was 105.48 and 86.52 million tons respectively. Total production of coarse cereals during 2014-15 was 42.86 million tonnes (Annual Report, Ministry of Agriculture and Farmers' welfare, Govt. of India, 2016-17).

Even after sufficient production of grains the food security issue needs to be addressed. Losses occurring after the harvest are one of the major evils demanding serious attention. Post-harvest losses mainly include losses due to inappropriate storage, lack of proper drying facilities, rough material handling, transportation and losses due to insects and rodents.

Nanda *et al.* (2012) reported the post-harvest losses occurring in grains during various unit operations and handling. Total losses in paddy, wheat and maize were found to be 5.2,6, and 4.1 % respectively. The total losses in pulses ranged from 6.36% (Pigeon pea) to 8.41% (Chick pea). Harvesting, threshing, storage at farm and processing units were identified as major contributors in total losses.

Table 2.1: Post-harvest losses during various unit operations in major cereals

Crop	Harvesting (%)	Collection (%)	Threshing (%)	Transportation (%)	Drying (%)	Total losses (%)
Paddy	1.2	0.7	1.1	0.1	0.2	5.2
Wheat	0.7	0.6	1.6	0.2	0.1	6
Maize	0.5	0.2	1.6	0.1	0.1	4.1

Kannan *et al.* (2013) studied that the postharvest losses across the food supply chain from harvesting of crop until its consumption. The losses can broadly be categorized as weight loss due to spoilage, quality loss, nutritional loss, seed viability loss, and commercial loss. Postharvest loss accounts for direct physical losses and quality losses that reduce the economic value of crop, or may make it unsuitable for human consumption. In severe cases, these losses can be up to 80% of the total production.

Sarkar *et al*. (2013) studied the post-harvest losses and found that a large amount of grains are lost as spillage during this operation, and grain losses during winnowing can be as high as 4% of the total production

Costa (2014) studied the post-harvest losses in maize and estimated losses as high as 59.48% in maize grains after storing them for 90 days in the traditional storage structures (Granary/Polypropylene bags).

Abass *et al.* (2014) studied post-harvest losses in parts of Africa and concluded that unseasonal rains or cloudier weather may restrict the proper drying, and the crop is stored at high moisture, which leads to high losses due to mold growth. About 3.5% and 4.5% losses were reported during maize drying on raised platforms in Zambia and Zimbabwe respectively.

Large amount of grain produced is lost due to improper handling and processing operations. Losses occurring during the drying operation can be reduced by using suitable drying technique and maintaining proper drying conditions it becomes essential to have suitable and efficient on farm dryers in order to minimise the losses occurring during drying.

2.2 Grain drying process

Grain harvesting is done at higher moisture content in order to minimise the shattering losses occurring at time of harvest. Harvested grains contain high moisture for safe storage. FAO recommended safe storage moisture content level for various grains in order to prevent its spoilage during storage according to the recommendations drying is an essential post-harvest process for efficient and effective management. For safe storage of paddy up to 6 months the grain moisture content should be 12% (db) and 10% (db) for values greater than 6 months. The values for maize are 15.5 % (db) and 13% (db) respectively.

Drying of grains occurs mainly in three stages. During the preheating period the drying slowly increases. When wet grain is exposed to hot air, only a very slight change in moisture is observed. This mainly happens because all the heat provided in the drying air is used to heat up the grain to the drying air temperature. In the constant-rate period the drying rate remains constant with time. Once the grain is at the drying temperature, water starts to evaporate from the surface of the grain. During this period, all the heat from the drying air is used to evaporate surface moisture and the amount of moisture removed from the grain is constant in time. In the falling-rate period the drying rate declines over time. As time passes, it takes more time for internal moisture to appear at the surface, and evaporation of water remains no longer constant in time. As a result, drying rate declines and some of the heat from the drying air heats up the grain. For paddy grain, the falling-rate period typically occurs at around 18% grain moisture content.

Lucia and Assenato (1994) reported maturity moisture content for various grains at the time of harvesting. The harvesting moisture content for paddy ranged from 23-28% whereas for wheat the same was 22-28 percent.

Availability of proper on farm drying facilities permits timely harvest and thus avoiding field losses. Secondly, it places the grain in a condition for safe storage as dry grain, thereby avoiding storage losses from molds and to an appreciable extent, from insects hence drying is the universal method of conditioning wet grain to preserve its quality and nutritive value for feed and food, and its germination for seed.

2.3 Various methods of grain drying

Methods of grain drying can be broadly classified as sun drying and mechanical drying. Selection of a drying method mainly depends on the drying temperature required for grain to be dried and economy of the process.

IRRI (2013) reported that sun drying is the most commonly practiced method for drying of grains in the developing country despite having many shortcomings. Sun drying is practiced in various forms like mat drying and pavement drying. Sun drying is labour intensive and has limited capacity. Temperature control is also difficult in this method and grains can easily be over heated causing cracked grain which leads to low milling quality. It is also not possible to sun dry at night or during rain

Kunze (2008) reported that the sun drying is usually a single pass operation which did not allow grain to go through a tempering phase to relieve internal stress as a result fissures were formed and significant grain damage was observed.

FAO reported that in field drying or stacking (field drying) the rice plants are often stacked in piles with the panicles inside to protect them from rain, birds and rodents, a practice that can lead to massive heat build-up inside the stacks. As a result molds grow quickly and infest the grains and discoloration usually develops within the first day of field drying. Another unwanted effect is that the relatively dry grains often absorb water from the wetter straw, which leads to fissuring of the dryer grains and thus reduces the potential head rice recovery. Sun drying of paddy is not reliable .the cost of drying in heated air dryers was estimated 5 times more than the sun drying process.

Alavi (2011) reported that mechanical drying addresses the limitations of natural drying, and offers advantages, such as reduction in handling losses, better control over the hot air temperature, and space utilization. However, they suffer with the limitations of high initial and maintenance cost, adequate size availability, and lack of knowledge to operate these dryers, especially with smallholders. Due to these limitations, these dryers are rarely used by smallholders in the developing countries.

Sontakke & Salve (2015) reported that sun drying takes longer time to dry grain to safe moisture levels compared to other mechanical and solar dryers. As the drying occurs in uncontrolled conditions the output product quality is poor and more often product obtained is contaminated by dirt, dust as well as by bacteria.

IRRI (2013) reported various advantages and disadvantages of various drying methods used for paddy. Dryer performance is described in terms of energy utilisation and the quality of dried products

Table 2.2: Comparison of various drying methods for paddy

Method	Crop flow	Drying technology	Advantages	Disadvantages
Field drying		Piles, racks	Inexpensive	Rapid quality reduction
Sun drying	Batch	Drying pavements or mats	Inexpensive, small scale operation, Local construction, Operation with unskilled labour	Labour intensive Typically poor milling quality
Heated air drying	Batch	Recirculatory bed dryer	Mixing of grain ,Large capacity range, Good quality	Skilled labourer requirement, Medium capital investment, Wear of moving components
Heated air drying	Continuous	Continuous flow dryer	Large capacity ,Economics of scale	High capital investment Not feasible for small batches of different varieties
In-Store Drying	Batch	Storage bin dryer	Excellent grain quality, Large capacity range	Pre-drying of high moisture grain, Risk of spoilage during power failure.

The various shortcomings present in the sun drying and mechanical drying promotes usage of solar dryers for drying of grains. Apart from utilising the green energy the solar dryer can also be equipped with air flow rate control and hence optimise the drying process to achieve good quality of final product.

2.4 Characteristics of Solar energy and solar potential of India

Solar energy is the largest exploitable renewable resource as more energy from sunlight strikes Earth in an hour than all of the energy consumed by humans in an entire year. This solar potential can be harnessed for drying of the grains in effective manner.

Ramachandra *et al.* (2011) reported that India has a vast potential for solar power generation since about 58% of the total land area (1.89 million km^2) receives annual average Global insolation above 5 $kWh/m^2/day$. Indeed, at present efficiency levels, 1% of land area is sufficient to meet electricity needs of India till 2031.The average intensity of solar radiation received over India is 200 MW/km^2 (megawatt per kilometer square) with 250–325 sunny days in a year. Solar energy intensity varies geographically in India, but the highest annual global radiation ($\geq$ 2400 kWh/m^2) is received in Rajasthan and northern Gujarat.

Veeraboina and Ratnam (2012) studied solar potential in India and reported that India has a great potential for solar power and it is estimated so many times of the energy requirement which is about 5000 trillion kWh per year. The solar radiation incident over India is equal to 4–7 kWh per square meter per day with an annual radiation ranging from 1200–2300 kWh per square meter. It has an average of 250–300 clear sunny days and 2300–3200 hours of sun shine per year. India's electricity needs can be met on a total land area of 3000 km^2 which is equal to 0.1% of total land in the country. The rate of energy received by the earth from solar energy is approximately 1, 20,000 TW .This is much high from both the current annual global energy consumption rate of about 15 TW and any additional requirement in future. Solar power is a clean, environmental friendly source of energy. There are no toxic by-products or emissions. Currently we are generating 4.59 % of solar energy of total produced renewable energy installed capacity in India.

India has tremendous potential to generate solar power. This solar power can be effectively utilised for drying of grains in a solar dryer. The cost of energy generated is very low and free from emissions thus adding value to its usage in drying.

2.5 Greenhouse dryers and its varied applications

Greenhouse dryer is an enclosed structure having transparent walls and roofs, made up of glass, polyethylene film etc. The product is placed in trays receiving the solar radiations through the plastic cover and moisture is removed by natural convection or forced convection. This technology improves the product quality and reduces the drying period.

Arun *et al*. (2014) studied the drying characteristics of coconut in Polanchi region of Tamil Nadu. They designed and fabricated a natural solar tunnel dryer. In March 2014, 5000 coconuts were dried. The main performance parameter were drying time and product quality and was observed that coconut which were having moisture of 53.84% wet basis were dried to final moisture of 7.4% wet basis in the solar tunnel greenhouse dryer for 56 hours but for drying in open sun it took 147 hours. The quality of dried coconut in solar tunnel greenhouse was good and was free from fungal and bacterial infection.

Sethi and Arora (2009) modified conventional even span type greenhouse solar dryer by using reflecting north wall. Performance evaluation was done by drying bitter gourd. The drying floor was 6m × 4m and enfolded with UV stabilised polythene sheet. Total drying time was saved by 13.33% and 16.67% by using inclined north wall in natural and forced convection mode respectively.

Rathore and Panwar (2010) developed a semi cylindrical solar tunnel dryer at College of dairy and Food Science Technology, Udaipur, India. Performance evaluation of the dryer was done by drying of 320 kg of seedless grapes in temperature range of 10-28^{0}C. In 7 days of drying period, moisture content of the sample was reduced 85% to 16%.

Janjai *et al*. (2011) developed parabolic shaped PV ventilated greenhouse solar dryer with black concrete floor. The drying floor area was 44m^2 and was enveloped with polycarbonate sheets. 52 W solar panel was provided to sun, 3 DC fans, 150 kg chillies were dried from initial moisture content 80% (wb) to 10% (wb) and drying period was found to vary from 24 hour to 84 hours.

Nayak *et al*. (2011) designed PV integrated greenhouse solar dryer installed at solar energy park IIT Delhi. The drying floor area was 2.5m×2.6m and was enveloped with UV stabilised polythene sheet. 3 DC fans were given for forced convection and the moisture content was reduced from 80% to 11% with a drying period of 21 hours compared to 26.67 hours in solar drying.

Adu *et al*. (2012) designed and fabricated a tent type solar dryer with drying platform along 2 long side walls are entirely enveloped with black cloth, while remaining two walls are half enveloped with black cloth. Roof was covered with transparent polythene. The performance evaluation of the dryer was done by drying Okra at temperature 50^0C. Okra was dried from initial moisture content of 86.65% to final moisture content of 3.43% and the drying time was 23 hours.

Kumar *et al*. (2013) evaluated roof even type greenhouse dryer under no load condition in both natural and forced convection mode. The drying floor area was 1.50×1.01 m^2 and was covered polycarbonate sheet of 3mm thickness. 2 vents of 0.01m diameter were given at bottom of dryer for air inlet under natural mode. It was found that forced convection efficiency of dryer increased by 2% as compared to natural mode of drying. Drying rate in forced convection was found to be 31% higher as compared to natural convection.

Greenhouse dryer trap the short wave radiations and generate sufficient required for drying of grains. It is a low cost dryer (compared to mechanical dryers) which can be used for on farm drying of grains if portability of the structure is improved.

2.7 Solar air inflated collector and its potential application in agricultural drying

Solar air heaters are flat-plate collectors (FPCs), consisting of an absorber, a transparent cover, and backward insulation. The performance of solar air heaters is mainly influenced by meteorological parameters (direct and diffuse radiation, ambient temperature and wind speed), design parameters (type of collector, collector materials) and flow parameters (air flow rate, mode of flow). These collectors could be put to use for drying applications in grain drying.

Chau *et al*. (1980) designed and tested a 104 m² inflated plastic solar air heater with black plastic suspended screens as the extended surfaces; comparisons were made to a solar air heater without screens. The collectors with two suspended plastic screens (as the extended surface) performed much better than collectors with only one suspended screen and exhibited more efficiency than collectors without a screen.

Fohr and Figueiredo (1987) studied several types of solar air collectors made from plastic film can be used for drying operations on farm (fodder, fruit, grain) etc. Agricultural solar collectors are classified as cylindrical or semi cylindrical plastic tunnels inflated by a constant flow of air, ventilated horticultural greenhouses. various methods of construction are a single black cylindrical film fastened to the ground with cords, double cylindrical film, film black and exterior transparent. The black film must be slid into the transparent film before inflating resulting in a transparent semi cylindrical tunnel with a black floor.

Koury *et al.* (2003) highlighted the use of inflatable solar collectors as energy solar absorbers for grain dry is a technically and financially workable solution to low the electrical energy consumption in this area. This collector is made by an absorber plate made by flexible black PVC and by one double cover made by flexible and transparent PVC. The solar collector reports a semi cylindrical format when air is injected in the confined space between the two covers' walls. The main advantages of the equipment studied are the low costs and its easy transportation. The mathematical model of the collector is obtained from the application of the conservation energy law on the four basic parts of the collector, which are, its absorber plate, the two covers and the air flowing inside the equipment.

Flores-Irigollen *et al.* (2004) presented a mathematical model to describe the dynamics of the heat transfer in an inflatable tunnel SAH. The thermal inertia of the PBS, which acts as the absorber surface, was defined by three equations to describe the temperature variations of the three components of SAH: the polyethylene cover, the heat transfer fluid (the air) and the absorbing surface of the collector. To validate the results, a few experimental tests were conducted in a 50 m long inflatable tunnel solar collector. The results of the presented model compared favourably with the experimental results.

Ruskis *et al.* (2011) investigated inflatable solar air heating collectors which were compact, lightweight, inexpensive, self-supporting and self-erecting/storing. Results found that the collector performance strongly depends on a number of entrance variables of the model (the air flow and air temperature at the collector entrance) and geometric equipment parameters (the collector length, the internal radiation at the inner surface of the cover and the space between both covers) .The internal radius of the inner surface of the cover, is another very important parameter in the construction of inflatable solar collectors. The collector efficiency increases as the distance between the covers increases. The explanation for this is that a larger distance between the covers generates a larger thermal insulation, with the disadvantage being the use of more material in the construction of the inflatable solar collector.

Baliram *et al*. (2015) analysed thermal performance of solar air dryer for three different absorber plates. During the course of study red chillies, mint and grapes were successfully dried in the solar dryer. In this experiment, various parameters were used in absorber plate such as solar air heater with absorber plate (Type I), solar air heater having wire mesh (Type II), and Solar air heater having aluminum fins (Type III). The payback period of the solar air dryer setup depends on overall cost of fabrication, maintenance cost and operating cost. The overall fabrication cost is Rs.17,970. The maximum thermal efficiency was achieved in this experiment in Type III, at air flow rate 4.20 m/s.

Inflatable Solar air collectors which work on the principle of greenhouse effect are lightweight, inexpensive, self-supporting and self-erecting. These collectors find potential application in drying however their suitability for grain drying needs further study.

2.8 Effect of various parameters on drying kinetics of grain

Drying kinetics of grain mainly depends on the grain structure, psychometric properties of the drying air and convective heat transfer coefficient of the drying air. Convective heat transfer coefficient depends on the air velocity of the drying air.

Aguerre *et al*. (1986) performed an experimental study to determine the effect of drying on quality of milled rice. It was found that with increase in drying temperature from 40- 70°C, degree of breakage during milling increased and RH decreased. Varying the air velocities between 0.26- 2.12 m/s had no effect on breakage.

Fan *et al*. (2000) studied drying of rough rice by drying the rough rice under three conditions: 43.5°C, 38% relative humidity (RH), 9.5% equilibrium moisture content (EMC); 51.7°C, 25% RH, 7.3% EMC; and 60°C, 17% RH, 5.8% EMC. Results showed that a decrease in moisture content of rice at the early drying stages did not substantially affect the head rice yield until a certain moisture level was reached. It appeared in this study that the amount of moisture that could be removed without affecting head rice yield increased as harvest MC increased.

Sarker *et al*. (2014) reported that in reducing paddy moisture content from 22% to 23% wet basis (wb) down to around 12.5% wb, , the specific electrical and the specific thermal energy consumption were found to be varied between 1.44 to 1.95 MJ/kg water evaporated and 2.77 to 3.47 MJ/kg water evaporated, respectively.

Analysis revealed that bed drying yielded 1–4% higher head rice yield while milling recovery and whiteness were comparable at acceptable milling degree and transparency. The bed air flow between 0.27 and 0.29 m^3/ s resulted in higher head rice yield slightly while its effect on drying time was not prominent so much. For paddy with initial moisture content below 23% wb, it is recommended that drying air temperature should not be higher than 39 °C in order to maintain rice quality at reasonable energy consumption.

Putra and Ajiwiguna (2017) studied the influence of air temperature and velocity for drying process higher air temperature and velocity increase the evaporation rate. However, the gradient of evaporation rate by temperature tends to decrease from 0.46 gram/°C to 0.2 gram/°C. Contrarily, the gradient is increased by velocity from 5 gram/ (m/s) to 9 gram/ (m/s). Based on this fact, it can be concluded that the effect of temperature is less significant at high air velocity.

Kumar *et al*. (2018) studied technical and financial performance was evaluated using a low cost modified STR dryer which has a capacity of 500 kg per batch. Four different air velocities such as 1.5, 2.0, 2.5 and 3.0 m/s were used for drying with temperature of 50 °C. The results showed that the temperature and moisture distributions in STR dryer were quite uniform. Duration of drying of paddy from 24.78 % to 8.5 % moisture content (wb) was 3.5–7 h depending upon the source of energy used. The operating cost of drying was found Rs. 1.23 per kg with electric based blower. At all the air velocities, the lowest value of lightness of colour was observed at air velocity of 3.0 m/s and the highest values were recorded at air velocity 2.0 m/s. The benefit-cost ratio and payback period were found 1.9 and 0.28 years for diesel engine operated STR dryer from the experiments at field level.

Optimum drying air velocity, temperature of drying air is important parameters that affect the grain kinetics and quality of dried product. Thus performance of a dryer depends on these parameters.

2.9 Physical properties of paddy variety Pusa Basmati 1121 (PB-1121)

The physical properties of the paddy variety helped in design and development of the dryer.

Patel *et al*. (2013) found out the physical properties of basmati paddy variety PB- 1121 at moisture content ranging from 22.5 to 9.5 % .The thousand grain mass, bulk density and angle of repose decreased from 29.94 to 22.24 g, 464 to 429 kg /m³ and 36.06 to 28.06 degrees, respectively while true density and porosity increased from 1366 to 1398 kg/m³ and 60.03 to 69.13%, respectively.

2.10 Economic analysis of solar dryer

Economics of the dryer helps to evaluate the cost and in selection of proper dryer for usage.

Nayak *et al*. (2012) conducted economic analysis of hybrid photovoltaic-thermal (PVT) integrated solar dryer. It was concluded that the total energy payback period for hybrid PVT solar dryer is 5.6 years, which is much less than the expected life of the dryer. Total benefits of dried cauliflower are calculated as Rs. 362 and benefits of dried product will be higher if large quantities of products are taken for drying.

Sengar *et al*. (2012) carried out economic evaluation of greenhouse for cultivation of rose nursery. The total construction cost of 80 m2 arch shape greenhouse was Rs.100000/-. Suitability of the economics of greenhouse, four economic indicators such as net present worth, internal rate of return, benefit cost ratio and payback period were calculated for rose nursery. Net present worth of investment made on greenhouse, the internal rate of return, the benefit cost ratio, when rose nursery grown inside the greenhouse were Rs.453221, 53%, 4.5 respectively.

Barnwal & Tiwari (2009) analyzed the cost of a hybrid photovoltaic greenhouse dryer. In this paper the hybrid greenhouse dryer has been used to dry grapes under forced mode of operation. The initial investment for Rs. 27,400 gives the lowest payback period of about 1.25 years and the cost of drying of the grapes is the lowest for initial investment of Rs.27,400 i.e. Rs.4.52 per kg as per the results of his work.

Sreekumar & Vijaykumar (2007) evaluated a roof-integrated solar air heating system for drying food stuffs. Detailed technical analysis was done on the system by four methods namely annualized cost, present worth of annual savings, present worth of cumulative savings, and payback period. The cost of drying 1 kg mango worked out to be Rs. 11 which was roughly half of that of an electric dryer. The payback period worked out to 0.54 year, much less than the estimated life of the system (20 years).

Fudholi *et al*. (2015) analyzed a techno economic solar drying system for seaweed in Malaysia. The results of economic analysis indicates that the double pass solar collector is best suited for marketing marine products as its payback period is as low as 2.33 years.

Demand of grains are ever increasing, loss of grains due to improper post-harvest handling leads to huge loss of capital and food. Cereals are generally harvested at moisture content of 20-23%, in order to store them for longer duration or ensure proper milling moisture content needs to be decreased. Sun drying which is the most practiced method despite being cheapest leads to poor dried product quality. India has great potential for solar energy and thus solar dryers can be effectively used for grain drying. Air inflated solar collectors which have the capability to trap the short wave and are flexible and low cost can be used as grain dryer. Need of a portable dryer operating on green energy and suitable for on farm drying of grains still prevails.

MATERIALS AND METHODS

Development of the solar powered air inflated grain dryer required proper selection of material followed by design of the drying chamber. Selected parameters affecting the dryer performance and drying characteristics were studied and the dryer was developed based on the optimum design parameters. The developed dryer was compared with sun drying in order to assess its performance in terms of the drying characteristics as well as quality of the end product. The materials used and methods followed in development and performance evaluation of solar powered air inflated grain drier are discussed under the following headings.

1. Selection of material for construction of solar powered air inflated grain dryer
2. Design of components of the dryer
3. Study of drying characteristics for selection of optimum design parameters (thickness of upper transparent sheet, inlet air velocity and grain bed depth)
4. Fabrication of the solar powered air inflated grain dryer
5. Performance evaluation of solar powered air inflated grain dryer
6. Statistical analysis of experiment data
7. Economic analysis of the developed dryer

3.1. Selection of material for construction of solar powered air inflated grain dryer

3.1.1 Selection of plastic sheet for construction of drying chamber

For the construction of base of the drying chamber, thick low density polyethylene sheet of 350 micron thickness was selected mainly due to its higher strength, rigidity and moisture impermeability. Black color of the bottom sheet allowed it to absorb the solar radiations falling and hence increase the temperature within the dryer.

The light weight of the sheet used promoted the portability of the dryer. For the construction of top of the drying chamber UV stabilized transparent low density poly ethylene sheet of two variable thicknesses (200 micron and 300 micron) was used. UV stabilized films have excellent capacity to withstand the solar radiations and have a long life (Dilara and Briassoulis, 2000). The transparent sheet allowed most of the radiations to pass through it and enter the dryer. Higher flexibility of the upper transparent sheet allowed the drying chamber to inflate smoothly and hence form a quonset tunnel while the air is blown through the chamber.

3.1.2 Selection of solar powered axial fan

The major requirement for the selection of fan was the air flow rate sufficient to ensure that structure doesn't collapse under low pressure and burst out under high pressure. The air flow rate should be sufficient to carry away the moisture evaporated during the drying process and hence ensure that no condensation takes in the drying chamber. The power consumption should be moderate. A solar power operated 12V DC axial fan (40 cm) diameter with 3 blades and high speed copper motor was selected. A DC fan speed regulator was provided which helped in varying inlet air velocity.

3.1.3 Frame for blowing unit

The frame for the blowing unit was made of angle iron (40×40×6 mm) due to its resistance to vibration, better stability and easy availability.

3.2 Design of components of the dryer

Main components of the dryer included the drying chamber and air blowing axial fan and regulator assembly.

3.2.1 Design of drying chamber

The design of the drying chamber was governed by the physical properties of the grain to be dried. Long Paddy variety Pusa Basmati (PB 1121) was selected for determining design values and evaluation of the dryer. The drying chamber of solar powered air inflated grain dryer was designed based on the amount of grain that was planned to be dried in order to study the effect of selected variables. The amount of grain is a function of grain depth and grain bulk density. The dryer was developed for drying 50-100 kg of selected variety of paddy grain in grain bed depths ranging from 2-4 cm which is the recommended depth for paddy drying. (IRRI, 2013).

Considering maximum bulk density of the selected variety paddy at harvesting moisture content *i.e.* at 22 % = 429 kg/m^3 (Nag *et al*., 2018).

$$\text{Volume of drying bed} = \frac{\text{Mass of paddy to be dried}}{\text{Desnsity of the paddy}} = 0.1165 \text{ m}^3$$

Since, the drying chamber was designed sufficient to hold the maximum amount of grain this resulted at the least depth of 2 centimeters. Considering, mass of paddy to be dried as 50 kg and average depth of grain bed while drying as 2 centimeters.

$$\text{Area of the drying bed} = \frac{\text{volume of drying bed}}{\text{average depth of grain bed while drying}} = 5.82 \text{ m}^2$$

A minimum width of 30 cm on each side of drying bed was provided for inflation of the drying chamber. The air blowing unit (solar powered axial fan) was run at the top speed and minimum distance to which it did not disturb the grain bed was evaluated. It was found that the grain bed placed near to 50 cm to the fan creates disturbance in the grain bed which affects the drying characteristics and stability of the structure. This additional space before the grain bed also allowed preheating time for the incoming air at ambient temperature.

Thus selecting, the length of the drying bed as 4.2 m and width as 1.4 m drying area,

$$\text{Drying area} = 4.2 \text{ m} \times 1.\ 4 \text{ m} = 5.88 \text{ m}^2$$

3.2.2 Volume of drying chamber

Knowledge of volume of drying chamber enables us in selection of air blowing unit and at the same time decide the optimum outlet size for efficient drying.

Volume of drying chamber = cross sectional area × length of the drying chamber

= (Area of the parabola + area of rectangle) × length of the drying chamber.

$$= \left(\frac{2}{3} \times a \times b + w \times H\right) \times L$$

Where a, b are base and height of parabola in the cross section respectively and w and H are width and height of the rectangular portion in the cross section. L is the total length of the drying chamber.

$$= \left(\frac{2}{3} \times 1.4 \times 0.5 + 1.4 \times 0.3\right) \times 5$$

$$= 4.43 \text{ m}^3$$

The amount of air the structure needed to remain inflated was 4.43 m^3. The air supplied by the axial was kept larger than the exhaust value for inflation of the structure.

Table 3.1: Specifications of the developed solar powered air inflated grain dryer

Parameters	Specifications (Depth 2cm)	Specifications (Depth 4cm)
Length of drying chamber	5m	5m
Width of drying chamber	2m	2m
Drying bed dimensions	4.2 × 1.4 m	4.2 × 1.4 m
Blowing unit	DC axial fan	DC axial fan
Maximum height of inflation	81 cm	81 cm
Drying area (m^2)	5.88 m^2	5.88 m^2
Capacity (kg)	50 kg	100 kg
Specific capacity per unit drying area (kg/m^2)	8.503	17.00
Diameter of axial fan (cm)	40	40
Air flow rate (m^3/h)	1356.48 (V = 3m/s) 678.24 (V = 1.5m/s)	1356.48 (V = 3m/s) 678.24 (V = 1.5m/s)
Specific air flow rate per dryer area ($m^3/h.m^2$)	230.69 (V = 3m/s) 115.34 (V = 1.5m/s)	230.69 (V = 3m/s) 115.34 (V = 1.5m/s)
Specific air flow rate per kg dried paddy/m^3.(h.kg)	27.16 (V = 3m/s) 13.56 (V = 1.5m/s)	13.56 (V = 3m/s) 6.78(V = 1.5m/s)

3.3 Study of drying characteristics for selection of optimum design parameters

In order to obtain the optimum operational conditions of the solar powered air inflated grain dryer two different level of each inlet air velocity grain bed depth and thickness of upper sheet was selected and their effect on drying rate and dryer performance was studied. Paddy (PB 1121) samples at nearly 22-23 % moisture content were dried at various treatment combinations of the selected parameters. The drying process was started at 9:30 AM and moisture depletion was recorded for every 30 minutes interval. All the experiments were replicated three times. The drying process was terminated at 5:00 PM and restarted at 9:30 AM next day. The tempering time provided was of 16 hours.

Table 3.2: Plan of experiment for selection of suitable top transparent sheet thickness, inlet air velocity and grain bed depth

Variables	Levels	Affected response variables
Thickness of upper transparent UV stablised sheet.	t_1 (200 microns) t_2 (300 microns)	Dryer thermal efficiency (%) Rise in temperature in dryer (°C)
Inlet air velocity	V_1 (1.5 m/s) V_2 (3 m/s)	Amount of moisture removed per unit time interval (kg/h)
Grain bed depth	D_1 (2 cm) D_2 (4 cm)	
Replications	R1, R2, R3	
Total Experiments	(2x3x2x3) = 24	

3.3.1 Selection of levels of variables in order to optimize the operating conditions

3.3.1.1 Thickness of the upper transparent sheet

The amount of heat trapped in the dryer and hence the temperature developed in it will depend on the transmittance characteristics of the upper transparent film and hence selection of upper sheet thickness affects the dryer performance. Upper thickness also affects the stability of the structure. 200 and 300 µm UV stabilized sheets were selected as variables because of their most common application in greenhouses and good strength along with poor water vapour transmission.

3.3.1.2 Inlet air velocity

Selection of levels of velocity was mainly guided by two factors. The lower level of velocity selected was sufficient enough to inflate the structure in short time. The higher velocity was selected based on stability of grain bed. The higher velocity didn't disturb the grain bed.

3.3.1.3 Grain depth

It is generally recommended practice for paddy grain to be dried in bed depth of 1- 4 cm. (IRRI, 2013).

3.3.2 Experimental location

All the experiments were conducted at energy laboratory, 28.63° N latitude and 77.2° E longitude and 228.61 m above mean sea level, located at Division of

Agricultural Engineering, ICAR- Indian Agricultural Research Institute, Pusa, New Delhi.

3.3.3 Sample preparation

The required amount of Pusa basmati (PB 1121) variety of paddy was procured from Seed Production unit, ICAR-Indian Agricultural Research Institute, New Delhi. The paddy procured was cleaned using air screen cleaner mainly to scalp the larger impurities and stones. Five samples each of 20 g were drawn and the moisture content was found out using hot air oven method. The initial moisture content was found out to be varying from 13–13.8 percent. The major objective of drying in grains is to remove the moisture present at the time of harvesting. In paddy harvesting moisture content ranges from 22–23 %. The calculated amount of water was added to the paddy in order to prepare the sample for drying.

Moisture was added in a two-step process in a batch of 5 kg. Calculated amount of water needed to bring the moisture content to 22 % was added to the batch by slow sprinkling and gradual churning of the paddy. In the first step the moisture was added to increase the moisture content up to 18 %, the 5 kg batch was kept in air tight sealed plastic bag at room temperature so that it doesn't attains equilibrium moisture content for a period of 16 h. In the second step further moisture addition was done following similar methodology and kept for another 16 h. Ten batches (50 kg) were prepared for the experiments involving a grain bed depth of 2 cm and 20 batches (100 kg) were prepared for experiments involving a grain bed depth of 4 centimeters.

3.3.4 Overnight Tempering of grain during drying process

Overnight tempering of grain helped the differences in grain moisture to equilibrate and hence reduce any moisture stress developing in the grain which may affect the quality. Tempering time was also essential as sufficient sunlight was not available after 5.00 PM to carry out the effective drying process. After allowing a tempering period of 16 h the drying was re started from 9:30 AM next day.

3.3.5 Collection of sample

The samples of paddy were collected at every 30 min time interval from five different points comprising of the four corners and the center of the drying chamber. Grain sample each of weight 5 g was collected from each point and stored in properly labeled aluminum container which was immediately sealed and weighted. The collected sample was put in hot air oven for determination of moisture content.

3.3.5 Parameters measured and instruments used

The following physical entities were measured during the experiment

3.3.5.1 Moisture content determination

The moisture content of the paddy sample was determined by hot air oven method following AOAC standards (Jindal & Siebenmorgen 1987). The samples collected at every half hour interval were kept in properly labeled aluminum boxes and weighted using Mettle Toledo weighing balance of least count 0.001 gram. The aluminum boxes were kept in the hot air oven for 16 hours maintaining a temperature of 130° Celsius. The samples were re weighted after 16 hours and difference in the weight gave the amount of moisture in the sample.

Weight of aluminum container (g) = W_1

Initial Weight of the grain sample collected = W_2

Initial Weight of the grain = W_2- W_1

Final weight of the sample = W_3

Final weight of the grain = W_3- W_1

Moisture content of the grain (wb) = $\frac{(W2-W1)-(W3-W1)}{W2-W1} \times 100$

(db) = $\frac{(W2-W1)-(W3-W1)}{W3-W1} \times 100$

Plate 3.1: Hot air oven for determination of moisture content

3.3.5.2 Current and voltage

For testing the performance of Solar PV system the current and voltage was measured for battery and inverter each by the multi meter (FLUKE 73 series multi meter) that provided the power output of Solar PV system.

$$\text{Power (W)} = V \times I.$$

3.3.5.3 Solar intensity

A measure of solar power falling on unit area, insolation (W/m^2) was measured at 30 min. interval with a thermoelectric pyranometer. Pyranometer was set in the same plane as the panel for instantaneous insolation measurements on panel surface (at tilt), and the reading was taken with the help of Solar Power Meter (KM-SPM-11).

3.3.5.4 Air velocity

The velocity of air flowing in and out of the dryer was measured using digital anemometer. Due to air flow the small rotating top in the anemometer generates magnetic impulse, transduced and displayed as precise wind speed.

3.3.5.5 Dry bulb and wet bulb temperature

Sling psychrometer was used for measuring the dry bulb and wet bulb temperature of drying air. Water is evaporated from the moist wick in the instrument bringing air to saturation and thereby recording the wet bulb temperature in the instrument.

3.3.6 Development of data logger for measurement of temperature and relative humidity

A microcontroller based data logging unit was developed for measurement and recording of drying air temperature and relative humidity inside the dryer and in ambient condition. The data logger was developed using Arduino Uno, DHT11 sensor, SD card module, RTC and LCD display. (Appendix XIV)

3.3.6.1 Buck converter (Step- down converter)

A buck converter (step-down converter) used was a DC to DC power converter which stepped down voltage (while stepping up current) from its input (supply) to its output (load). It consists of a switched-mode power supply (SMPS) which contained two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination.

3.3.6.2 Real-time clock (DS3231)

Real time clock was used in order to display the time of measurement and recording in the developed data logger. The DS3231 used was a low-cost, extremely accurate I^2C real-time clock (RTC) with an integrated temperature compensated crystal oscillator and crystal. The device incorporated a battery input and maintains accurate timekeeping when main power to the device interrupted.

3.3.6.3 Micro SD card Module

The module (Micro SD Card Adapter) used was a Micro SD card reader module for reading and writing through the file system and the SPI interface driver.

3.3.6.4 Liquid-Crystal Display

A liquid-crystal display (LCD) was used for display of the temperature and relative humidity developed in the dryer.

3.3.6.5 Aurduino Mega

The Aurduino Mega used was a microcontroller board based on the ATmega2560. It had a USB host interface to connect with Android based phones, based on the MAX3421e IC. It had 54 digital input/output pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button.

3.3.6.6 DHT 11 sensors

Digital temperature and humidity sensor DHT 11 was used which was a composite sensor containing a calibrated digital signal output of the temperature and humidity. The sensor included a resistive sense of wet components and NTC temperature measurement devices, and connected with a high-performance 8-bit microcontroller. The major reasons behind the selection of the sensors were its low cost, long-term stability, relative humidity and temperature measurement, fast response, strong anti-interference ability, long distance signal transmission, digital signal output, and precise calibration.

3.3.6.7 Sensor positioning

Three DHT 11 sensors were placed in the dryer in order to measure the temperature and relative humidity of the drying air. The sensors were placed at distance of 1m, 2.5 m and 4m from the air entry side. The sensors were hung with the help of connecting wire to a height of 40 cm from the top. Before placing the sensors were properly calibrated with mercury in glass thermometer for temperature calibration and sling psychrometer for calibration of relative humidity. For the developed data logger unit used in measuring the temperature and RH, a 12 V battery was used to provide the power.

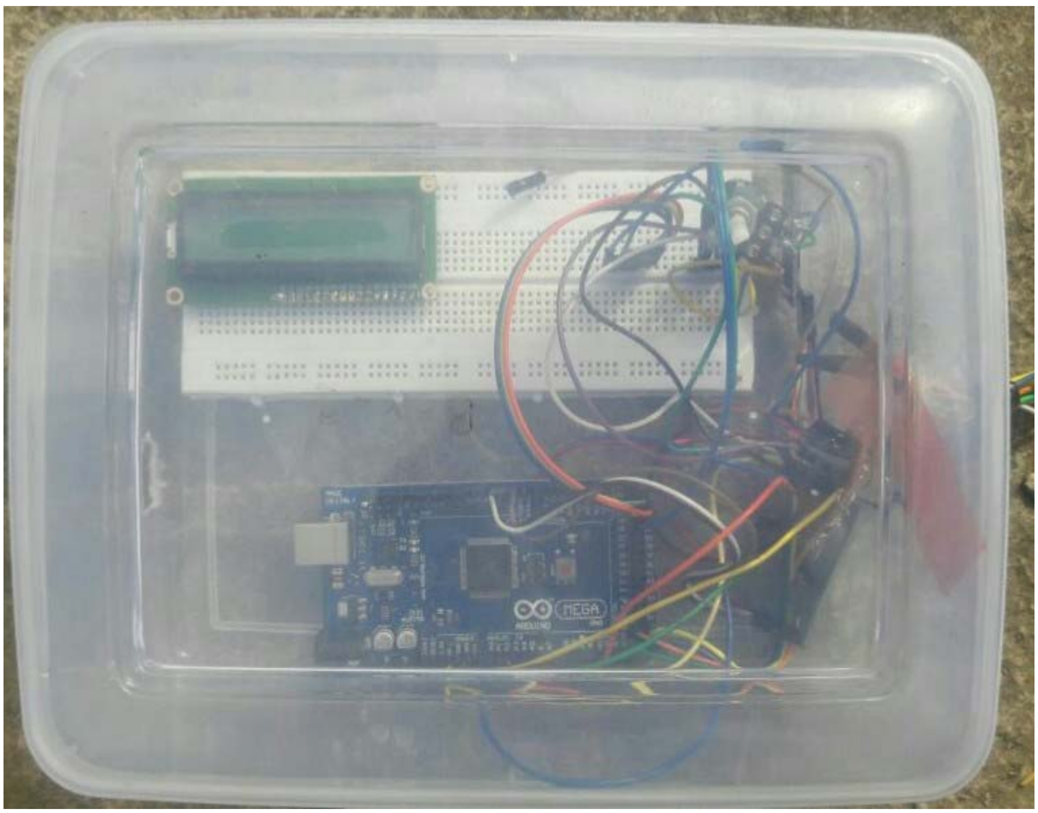

Plate 3.2: Developed data logger for measurement and recording of temperature and relative humidity

3.3.7 Optimisation of design parameters for dryer

The thermal efficiency of dryer, temperature rise developed in the drying air and amount of moisture removed were selected in order to optimize the operating condition for the developed dryer.

3.3.7.1 Determination of dryer thermal efficiency

Thermal efficiency of the dryer encompasses the attributes of amount of moisture removed and the temperature rise that is developed in the air inflated solar powered grain dryer as a result of solar radiations. (Seetapong *et al*.,2017) Thermal efficiency was calculated as:

$$\eta_{\text{thermal}} = \frac{\text{Mw} \times \text{Hv}}{\text{Ms} \times \text{Cs} \times (\text{Td} - \text{Ts})} \times 100$$

Where, Mw = amount of moisture removed from the grain.

Hv = latent heat of vaporization of water at drying temperature

Ms = total air flow in the drying chamber

Cs = specific heat of ambient air (1.005 + 1.88 × H) kJ/ kg °C

H is the ambient relative humidity of the air.

Td = average drying air temperature in the dryer

Ts = temperature of ambient air

3.3.7.2 Determination of rise in temperature of the drying air

The optimum temperature for drying of paddy should range from 45-50°C. (FAO, 1991) and thus it was important to consider the rise in temperature that is being produced in the dryer as a result of greenhouse effect. The upper transparent sheet trapped the solar radiations thereby increasing the temperature in the drying chamber. The rise in temperature pf drying air was calculated as:

$$\Delta T = Td - Ts$$

3.3.7.3 Determination of moisture removal rate

Grain samples (20 g) were collected at every 30 minutes interval and moisture content was measured using gravimetric method. The difference in moisture content was measured of the grain sample, measured at two successive time intervals was used for calculating moisture removal rate.

3.4 Fabrication of solar powered air inflated grain dryer

Based on the optimum design values obtained solar powered air inflated grain dryer was fabricated in Workshop and Energy Laboratory, Division of Agricultural Engineering, ICAR- IARI, New Delhi.

3.4.1 Fabrication of the drying chamber

The drying chamber was designed depending on the batch capacity while drying paddy grain The base of the drying chamber was constructed with a black thick polyethylene sheet (350 µm) whereas the top of the drying chamber was made from transparent polyethene sheet of two variable thickness (200 and 300 µm). (Plate 3.3).The flexibility of the upper sheet was ensured for proper inflation of drying chamber when air flows across it. A heavy duty zipper was used to join the bottom and upper halves which also facilitated opening and closing for loading and unloading the grain in the dryer.

Plate 3.3: Fabricated drying chamber of solar powered air inflated grain dryer

3.4.2 Fabrication of frame

Angle iron (40 × 40× 6 mm) was used to fabricate frame for holding the axial fan and speed regulator assembly. Two (10 m) long angle iron bars were cut into the specified dimensions using metal cutting saw. The iron bars were gas welded to construct the frame. The frame cross section dimensions (70 cm×70 cm) were decided based on the diameter of fan and clearance required from the ground in order to blow sufficient air in the drying chamber. The weight of the developed frame was 15 kg making it portable for on farm drying. Fan was clamped at the center for easy attachment, detachment and better portability of the unit, Figure 3.1.

Table 3.3: Design specifications of frame for axial fan and regulator assembly

Materials used	Angle iron (40 × 40× 6 mm)
Length	70 cm
Width	60 cm
Height	70 cm
Clamping height	20 cm

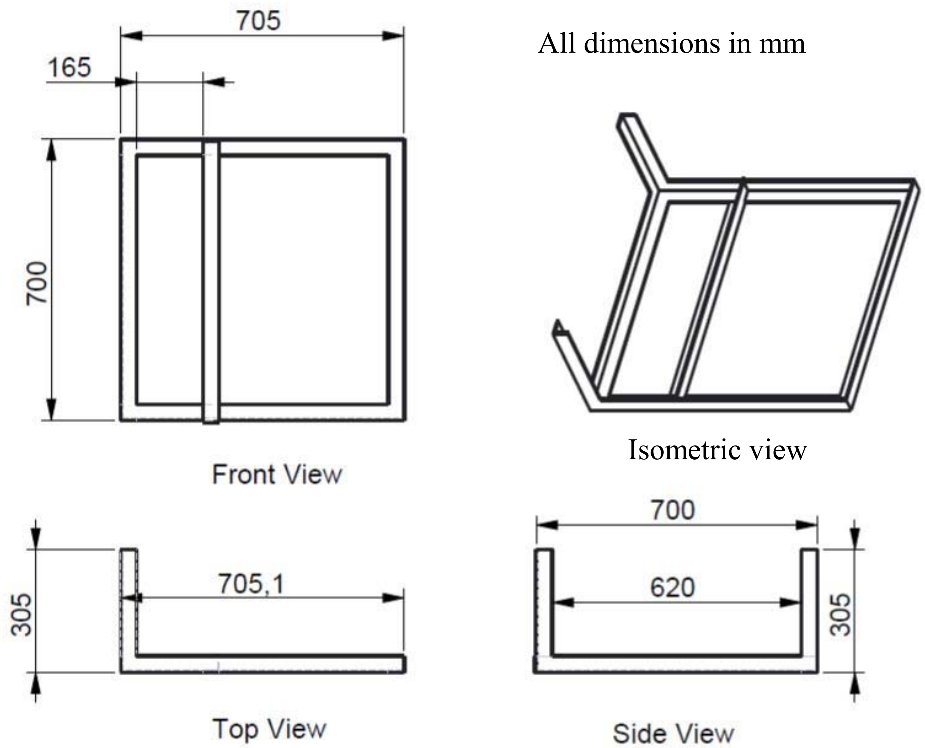

Figure 3.1: Design of Frame for fan and regulator assembly

3.4.3 Fabrication of Grain mixing rake

To facilitate uniform drying a grain mixing rake was developed at Workshop, Division of Agricultural Engineering, ICAR-IARI, New Delhi and thorough mixing was done during the experiment every hour (IRRI, 2013).

3.4.4 Fabrication of air exhaust unit

Suitable outlet for carrying the moisture away was provided at the trailing side with a sliding arrangement provided in order to vary the amount of air escaping through the drying chamber Nine equi-dimensional circular holes each of 2 cm diameter were drilled in an aluminum plate of 15×15 centimeters. The aluminum plate was riveted to the bottom plastic sheet using 5/16” rivets. A sliding gate arrangement was provided in order to facilitate varying outlet area depending upon inlet air velocity and load in the drying chamber. Aluminum metal was used for construction of outlet unit because of its light weight which doesn’t add further weight on the inflating portion and hinder the inflation of the drying chamber. (Plate 3.4)

Area of 1 circular hole at outlet = $\frac{3.14 \times (0.02\ \text{m})^2}{4}$ = 3.14×10^{-4} m²

Total area open at outlet = 3.14×10^{-4} m² × 9 = 28.26×10^{-4} m².

Plate 3.4: Fabricated air exhaust unit

3.4.5 Development of structural support system

Four strips of Velcro (5 cm wide), two at the upper transparent sheet and two at bottom black sheet with tying arrangement at the frame of the fan ensured the stability of the structure. The support arrangement was riveted to the sheets for strength. The Velcro held the drying chamber firm while it was being inflated.

3.4.6 Selection of power supply for the developed dryer

The developed dryer utilized solar energy for operation of the axial fan. Solar panel (NS36P4-100 W) was used to generate power from the solar energy which operated the fan. A charge controller (Solar Max 371) was also used in the power supply system to ensure uniform voltage preventing overload during intense sunshine hours.

Table 3.4: Solar panel specifications used for operating the axial fan in the developed dryer

Parameters	Specifications
Maximum power	100 W
Open circuit voltage	21.60 V
Short circuit current	6.04 A
Voltage at maximum power	17.64 V
Current at maximum power	5.72 A
Panel dimensions	1149 × 665 × 35 mm

3.5 Performance evaluation of the solar powered air inflated grain dryer

The developed dryer was evaluated for its performance and quality of the product after drying in comparison with sun drying which was the most widely used method of drying the grains in rural areas. (Table 3.4) The comparative performance evaluation of the developed solar inflated grain dryer was done at Energy laboratory, division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi.

Sample each of 100 kg paddy (PB-1121) with initial moisture content 22±0.3% was dried in solar powered air inflated grain dryer and sun drying on the concrete floor simultaneously. The grain bed maintained during drying was 4 cm in both solar powered air inflated grain dryer and sun drying. 5 g of grain samples were collected from four corners and center at every 30 min. time interval from the dryer and sun drying which was used for determination of moisture content and the drying rate. The sun drying process occurred at ambient temperature.

Table 3.5: Parameters considered for performance valuation of developed dryer and sun drying

Parameters	Developed dryer	Sun drying
Drying air temperature	T_d	T_a
Rate of drying	R_{d1}	R_{d2}
Milling rice yield	MRY_d	MRY_{sd}
Head rice yield	HRY_d	HRY_{sd}
Replications = 3		

Plate 3.4: Developed solar powered air inflated grain dryer

Plate 3.5: Grain bed in the drying chamber

Plate 3.6: Comparative evaluation of developed dryer and sun drying

The different performance parameters were evaluated as following

3.5.1 Milling quality

A sample of 150 g was collected from both sun drying and the developed dryer at the end of drying i.e. on attainment of 14% moisture content. The collected samples were de husked in rubber roll Sheller (Model C). The average grain size of the paddy variety PB 1121 was 14. 68 mm. The de husked rice of size greater than or equal to 11.01 mm (75% of original length) was taken as head rice. The head rice and broken were separated manually and weighted to determine the milling recovery yield and head rice yield. Milling recovery yield (MRY) defined as the percentage of finished product (brown rice) obtained from de husking of the paddy calculated as:

$$\text{MRY} = \frac{\text{Weight of milled paddy}}{\text{Weight of initial sample}} \times 100$$

Head rice yield (HRY) defined as the mass of head rice expressed as a percentage of the original rough rice mass:

$$\text{HRY} = \frac{\text{Weight of head rice}}{\text{Weight of initial sample}} \times 100$$

3.6 Statistical analysis of collected data

The statistical package SAS was used to analyse the experimental data and hence optimise the operating conditions for the dryer. This was done to obtain the necessary analysis of variance of the mean and interaction of the selected variables. The experimental data was analysed using Latin square design.

3.7 Economic analysis of the developed dryer

Cost of construction of the dryer was calculated by adding the cost of various components, labour charges during construction. Repair and maintenance charges were assumed to be 3 % of the total cost of construction (Sajith, 2014).

Chapter 4

RESULTS

A solar powered air inflated grain dryer was developed using the optimum operating conditions which were determined by two different thickness of upper transparent UV stabilised polyethene sheet (200 µm and 300 µm), two levels of inlet air velocities (1.5 m/s and 3 m/s) and two depths of grain bed while drying (2 cm and 4 cm). Different combinations obtained from the selected variables were compared with respect to three different parameters of thermal efficiency of the dryer, the temperature rise in the drying air and the amount of moisture removed per unit time.

The developed dryer was evaluated with respect to dryer performance and dried product quality parameters. The performance parameters like the temperature developed in the dryer and drying rate were compared with sun drying. Paddy (PB1121) was dried in the developed dryer in order to evaluate its performance. The milling yield and the head rice yield were also compared in order to access the quality of produce dried in the developed drier compared to that under sun drying. The results obtained have been presented in this chapter.

4.1 Study of drying characteristics for selection of optimum design parameters

4.1.1 Solar insolation and power generated

Average solar intensity was measured at surface (tilt) of solar PV panel (1.1 m × 0.6 m) at every 30 minutes interval from 9:30 AM to 5:00 PM for each experiment (Appendix I). The average solar intensity measured was 614 W/m² and the peak value of solar intensity occurred between 12:30 PM to 1 PM with an average value of 720 W/m².The average voltage and current observed were 16.51 V and 3.55 A respectively (Appendix II). The developed power was helpful in selecting the suitable panel size for operating the axial fan.

4.1.2 Temperature and relative humidity developed in the dryer

Temperature of ambient air was found to be dependent on the solar intensity. The maximum ambient temperature was recorded between 2 PM and 2:30 PM. Temperatures measured at different length intervals (1m, 2.5m and 4m) showed that temperature measured at 2.5 m length had the highest value (Appendices III-X). The relative humidity of ambient air was found maximum at the morning and gradually decreased to lowest value between 3:30 PM to 4:00 PM. After 4 PM an increasing trend was observed in ambient air relative humidity (Appendices III-X). The relative humidity of drying air at point 1m from the inlet end was found to be lower than the ambient air because of the rise in temperature.

4.1.3 Effect of selected variables on thermal efficiency of the solar powered air inflated grain dryer

Thermal efficiency of the dryer was calculated at every 30 minutes interval for two different levels of thickness of upper transparent sheet, inlet air velocity and grain bed depth. Analysis of variance conducted at 1% level of significance for thermal efficiency of the dryer and it was found that varying the thickness of upper transparent sheet had no significant effect (P=0.0583) on the thermal efficiency, Table 4.1.

Table 4.1 ANOVA of thermal efficiency

Source	DF	Type I SS	Mean Square	F Value	P > F
Thickness of upper transparent sheet (t)	1	568.79	568.79	3.60	0.0583
Inlet air velocity (v)	1	35243.88	35243.8	223.06	<.0001
Grain bed depth (D)	1	19619.81	19619.8	124.17	<.0001
t*V*D	4	7625.84	1906.46	12.07	<.0001
Error	529	83583.97	158.003		
Corrected Total	536	146642.30			

Significant difference was found in the thermal efficiency when inlet air velocity (P<.0001) and grain bed depth (P<.0001) were changed.

Least mean square value was calculated for each treatment combination and it was found that treatment combination of upper transparent sheet thickness (300 µm), inlet air velocity (3 m/s) and grain bed depth(4cm) showed highest thermal efficiency. The lowest thermal efficiency was achieved in case of upper transparent sheet thickness (200 µm), inlet air velocity (1.5 m/s) and grain bed (2 cm). The least square mean value of thermal efficiency was found to vary from 18.92-45.75%. Higher thermal efficiency is an indicator of better moisture removal in the dryer, Table 4.2.

Table 4.2: Least mean square values of thermal efficiency for combination of various levels of selected variables

Treatment combination	Thickness of upper transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square Mean
1	200	1.5	2	18.92
2	200	1.5	4	26.59
3	200	3	2	30.92
4	200	3	4	45.32
5	300	1.5	2	21.35
6	300	1.5	4	23.93
7	300	3	2	28.56
8	300	3	4	45.75

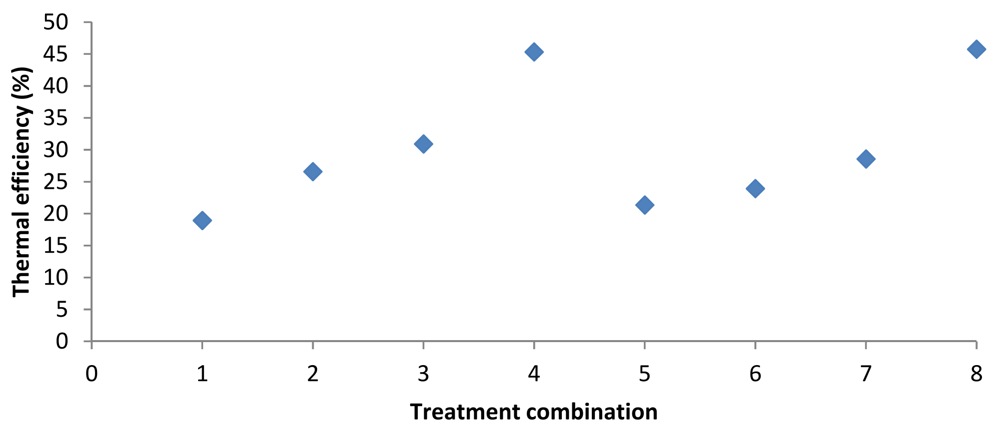

Figure 4.1: Scatter chart of least square mean for the thermal efficiency in different treatment combinations

Scatter plot diagram, Figure 4.1 of least square of means for thermal efficiency in various treatment combinations of upper transparent sheet thickness, inlet air velocity and grain bed depth. The least square of mean for thermal efficiency was found to increase with increase in inlet air velocity and grain bed depth.

4.1.3 Effect of selected variables on temperature rise of drying air in the solar powered air inflated grain dryer

Temperature rise of the drying air was calculated by difference of average drying temperature and ambient air temperature. Analysis of variances, Table 4.3 showed that increasing the inlet air velocity (P=0.4166) had no significant effect on the temperature rise in the drying air. Increase in the upper transparent sheet thickness and grain bed depth both were found to have significant effect on temperature rise in the drying air.

Table 4.3: ANOVA of temperature rise in the drying air

Source	DF	Type I SS	Mean Square	F Value	P>F
Thickness of upper transparent sheet	1	123.77	123.77	109.88	<0.001
Inlet air velocity	1	0.7446	0.74	0.66	0.4166
Grain bed depth	1	136.82	136.82	121.47	<0.001
Thickness of upper transparent sheet	4	63.32	15.83	14.05	<0.001
Error	529	595.86			
Corrected Total	536	920.52			

Upper transparent sheet thickness (300µm), inlet air velocity (3m/s) and grain bed depth (4 cm) was found to result in highest temperature rise. The least square mean value of rise in temperature of drying air was found to vary from 3.35-5.81°C. Table 4.4.

Table 4.4: Least mean square values of rise in temperature of the drying air for combination of various levels selected variables

Treatment combination	Thickness of upper transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square Mean (°C)
1	200	1.5	2	3.35
2	200	1.5	4	4.24
3	200	3	2	3.71
4	200	3	4	4.56
5	300	1.5	2	4.99
6	300	1.5	4	5.42
7	300	3	2	3.82
8	300	3	4	5.81

Scatter chart of rise in temperature of drying air shows the increase in the value of temperature rise with increase in grain bed depth and upper transparent sheet thickness, Figure 4.2.

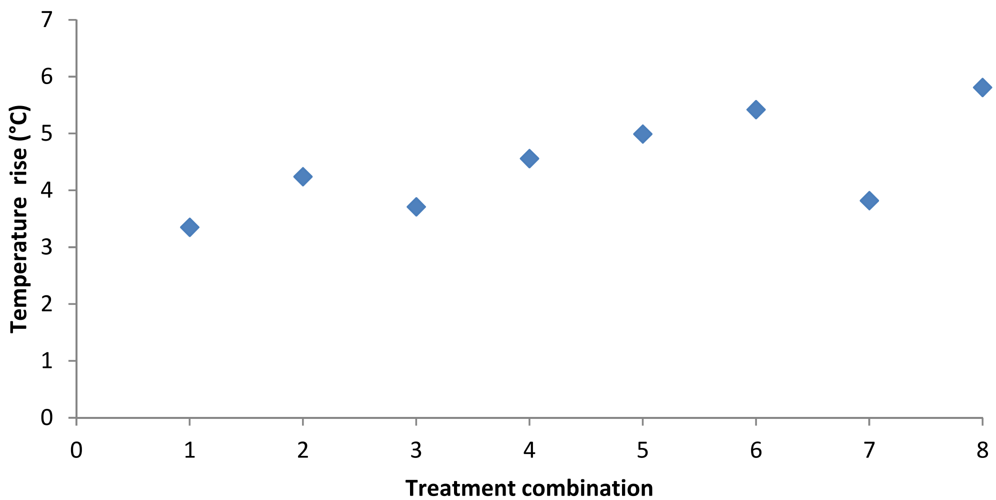

Figure 4.2: Scatter chart of least square mean for the thermal efficiency in different treatment combinations

4.1.4 Effect of selected variables on amount of moisture removed per unit time interval for paddy in the solar powered air inflated grain dryer

Amount of moisture present in the collected sample for all combinations of different levels of thickness of upper transparent sheet, inlet air velocity and grain depth were recorded and decrease in the moisture content with time was plotted against time. The desired moisture reduction(from 22% to 14% wb) was achieved on the first day when the upper transparent sheet thickness (300 µm), inlet air velocity (3 m/s) and grain bed depth (4 cm) combination was used. It was found that average drying time ranged between 7.5 hours to 11 hours. Amount of moisture removed was calculated by using the difference in moisture content measured at every 30 minutes interval, Figure 4.3

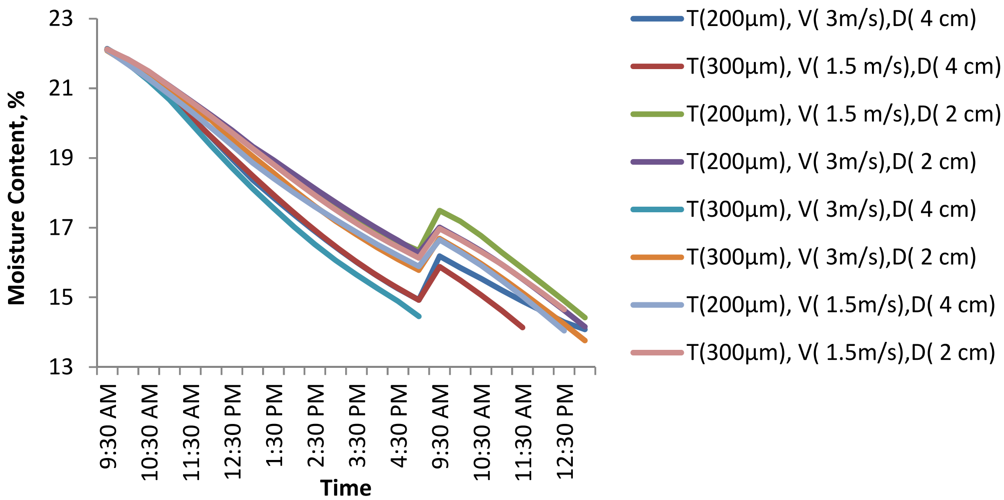

Figure 4.3: Drying rate curves sample for all combinations of different levels of selected variables

Analysis of variances, Table 4.5 showed that increasing the inlet air velocity (P=0.7240) and the thickness of upper transparent sheet (P=0.0139) had no significant effect on amount of moisture removed per unit time interval of paddy in the solar powered air inflated grain dryer**.**

Table 4.5: ANOVA of amount of moisture removed per unit time

Source	DF	Type I SS	M.S	F Value	P > F
Thickness of upper transparent sheet	1	0.285	0.285	6.09	0.0139
Inlet air velocity	1	0.005	0.00585	0.12	0.7240
Grain bed depth	1	24.4	24.47	522.33	<.0001
t*V*D	4	1.30	0.32	6.98	<.0001
Error	529	24.7	0.046		
Corrected Total	536	50.8			

The least mean square values indicate that the amount of moisture removed was highest for upper transparent sheet thickness (300 µm), inlet air velocity (3 m/s) and grain bed depth (4 cm), Table 4.6. The moisture removed per unit time varied from 0.36-0.95 kilograms/hour.

Table 4.6: Least mean square values of amount of moisture removed per unit time interval for combination of various levels of selected variables

Thickness of upper transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square Mean
200	1.5	2	0.38
200	1.5	4	0.72
200	3	2	0.38
200	3	4	0.73
300	1.5	2	0.38
300	1.5	4	0.85
300	3	2	0.36
300	3	4	0.95

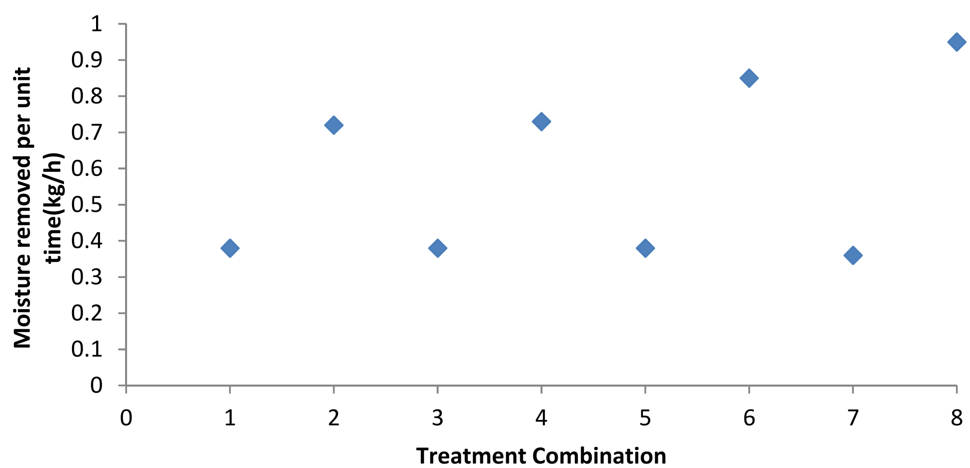

Figure 4.4: Scatter chart of least square mean for the moisture removed per unit time in different treatment combinations

Scatter chart showed that upper transparent sheet thickness (300 µm), inlet air velocity (3 m/s) and grain bed depth (4 cm) yielded highest least mean square values for all the three parameters considered. The moisture removed per unit time was highly scattered showing its variation with grain bed depth and inlet air velocity, Figure 4.4.

4.2 Performance evaluation of solar powered air inflated grain dryer

Using the results obtained the solar powered air inflated grain dryer was developed and its performance was analysed compared to sun drying.

4.2.1 Drying air temperature developed in the dryer compared to sun drying (Ambient air)

The temperature of drying air in the developed dryer was found to increase with time reaching its peak value at 1.00 PM. The temperature of drying air ranged between 29.8-38.2 °C compared to ambient air temperature ranging from 25.7-34 °C, Figure 4.5. Analysis of variances showed that there was significant difference (P <.0001) in the drying air temperature in the dryer when compared with the sun drying (ambient air temperature), Table 4.7.

Table 4.7: ANOVA of drying air temperature

Source	Degree of freedom	SS	Mean Square	F Value	P> F
Treatment	1	622.45	622.45	55.30	<.0001
Replication	2	20.65	10.32	0.92	0.4021
Error	124	1395.6	11.25		
Corrected Total	127	2038.79			

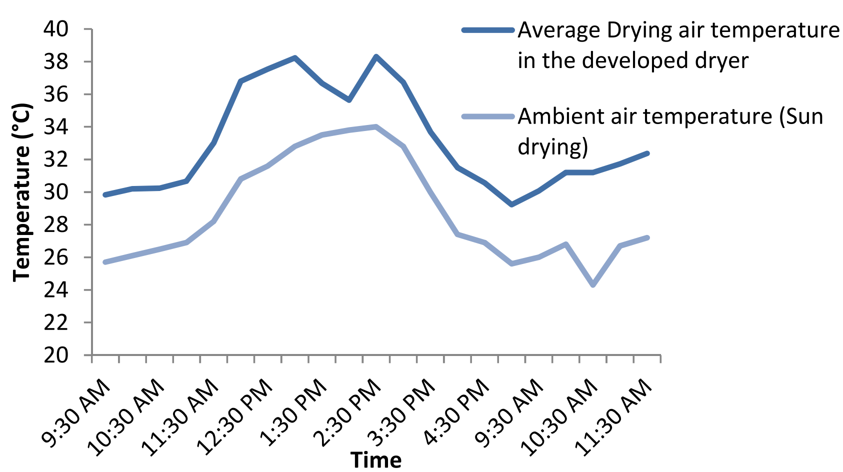

Figure 4.5 Temperature profile of average drying air temperature in the developed dryer and during sun drying

4.2.1 Drying rate for paddy grain in the developed dryer and sun drying

The time required for reduction in moisture content from 22% to desired 14% in paddy was found lower in case of drying carried out by the developed dryer. The drying rate values (Appendix XII) were also higher compared to sun drying. In case of the developed dryer and sun drying the amount of moisture removed in given time interval ranged from 0.5-1.24 kg and 0.64-0.92 respectively, the desired moisture reduction from 22% to 14% was completed in 7.5-9 hours in the developed dryer compared to 11-12.8 hours in sun drying. Figure 4.6.

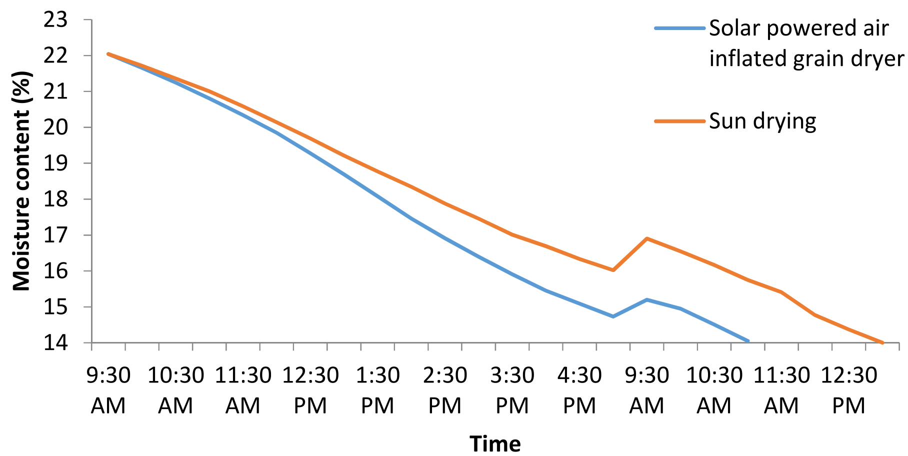

Figure 4.6 Moisture content of paddy at various time intervals in the developed dryer and during sun drying

The drying rate for paddy was calculated at each 30 minute interval and comparison was made between the developed dryer and sun drying. It was found that the drying rate in the developed dryer was significantly different (P=0.0019) as compared to sun drying, Table 4.8.

Table 4.8: ANOVA for drying rate

Source	Degree of freedom	SS	Mean Square	F Value	P > F
Treatment	1	0.79	0.797	10.05	0.0019
Replication	2	0.08	0.042	0.53	0.5884
Error	123	9.75	0.079		
Corrected Total	126	10.641			

4.2.2 Quality of the dried product

The dried paddy was de husked and its quality was evaluated on the milling yield and head rice yield obtained. Analysis of variances at 5% level of significance. Table 4.9 showed that there was no significant difference (P=0.033) in the milling yield produced in the paddy dried in the developed dryer compared to sun drying but head rice yield of paddy dried in the dried showed significant difference (P = 0.002) compared to the sun drying, Table 4.10.

Table 4.9: ANOVA for milling yield

Source	SS	DF	MSS	F value	P > F
Between groups	9.677	1	9.677	10.41	0.033
Within groups	3.818	4	0.954		
Total	13.49	5			

Table 4.10: ANOVA for Head rice yield

Source	SS	DF	MSS	F Value	P > F
Between groups	51.081	1	51.081	56.263	.002
Within groups	3.632	4	0.908		
Total	54.712	5			

4.3 Cost Analysis

Table 4.11: Cost of various components of solar powered air inflated grain dryer

Component	Cost (Rupees)
Upper transparent UV stablished polyethene sheet	800
Bottom thick black polyethene sheet.	900
Axial fan (solar powered DC)	1900
Metal frame	300
Heavy duty zipper	250
Mixing rake	400
Miscellaneous cost	200
Manufacturing cost	800
Solar panel	5300
Total cost	10850

The total cost in manufacturing of dryer was Rs. 10850

Number of days the dryer can be used for various grain crops = 300 days

Operational hours /day (depending on sunshine availability) = 8

Total working hours in a year = 2400 hour

Total cost of the dryer was calculated based on adding up the cost of individual components and the labour required in the fabrication process. Time taken the dryer for reduction of moisture from 22% to 14% (wb) was 9.5-11 hours and thus the dryer can be used for drying a batch per day of 100 kg paddy. The developed dryer can also be operated for other agricultural products.

Chapter 5

DISCUSSION

Following chapter deals with the detailed discussion on various results obtained from the study.

5.1 Study of drying characteristics for selection of optimum design parameters

5.1.1 Temperature and relative humidity of ambient air and drying air in the dryer

The drying air temperature in the dryer was found to higher than the ambient air because of the greenhouse effect (trapping of the solar shortwave radiations by the transparent upper sheet). The major reason behind the temperature rise is ample residence time for the drying air to get heated. The temperature at point 4 m along the length was found to be lower than the temperature measured at 2.5 m because of the cooling effect produced due to gain of moisture as a result of drying. The relative humidity was found to increase at point 2.5 m and 4 m along the length because of the gain of moisture as the drying progressed. The measured relative humidity of drying air was found highest at point 4m along the length.

5.1.2 Effect of selected variables on thermal efficiency of the solar powered air inflated grain dryer

As the thickness of upper transparent sheet increased the temperature rise in the dryer was higher and the amount of moisture removed also increased. The deeper grain bed depth resulted in more amount of grain in the batch drying process and thus more moisture was removed while drying. This resulted in high thermal efficiency of the dryer in grain bed depth (4cm). Greater air inlet velocity resulted in carrying the evaporated moisture faster maintaining the gradient between saturation humidity and absolute humidity of the drying air thus resulted in higher values of thermal efficiency.

5.1.3 Effect of selected variables on temperature rise of drying air in the solar powered air inflated grain dryer

The rise in temperature was higher when the thickness of upper sheet was increased from 200 μm to 300 μm mainly because thicker sheet produced more greenhouse effect. Similar trend was explained by an analysis conducted by Boldrin (1985) where the greenhouse effect was found to increase from 20 to 30 % on increasing the thickness of polyethene sheet from 100 μm to 200 μm.

5.1.4 Effect of selected variables on amount of moisture removed per unit time interval for paddy in the solar powered air inflated grain dryer

The air inlet velocity of 1.5 m/s was sufficient to carry away the moisture evaporated in the drying chamber thus increasing the inlet air velocity had no significant effect on the drying rate. Increasing the grain bed depth had significant effect on the amount of moisture removed per unit time. This was because the amount of moisture removed was higher in case of higher grain bed depth, since larger quantity of grain was dried expelling out larger amount of moisture in unit time. Increasing the upper transparent sheet thickness led to increase in the temperature of drying air and hence amount of moisture removal increased significantly.

5.2 Performance evaluation of solar powered air inflated grain dryer

Performance of the developed solar powered air inflated grain dryer was accessed in comparison with sun drying.

5.2.1 Drying air temperature developed in the dryer compared to sun drying (Ambient air)

Greenhouse effect produced by the upper transparent UV stabilised sheet was the major reason behind the rise in temperature in the dryer. Suitable dying temperature for paddy grain is 45-50 °C.

5.2.2 Drying rate for paddy grain in the developed dryer and sun drying

The major reasons behind increased rate of drying are the rise of temperature of the drying air and forced convection flow which carries away the moisture at a desirable rate. The time saved in the operation is crucial as it allows more quantity of the grain to be dried in short time preventing their spoilage. Higher drying temperature resulted in more moisture removal in paddy in unit time. Similar trends were observed by Putra and Ajiwiguna (2017), higher air temperature and velocity increase the evaporation rate. Sigge *et al.* (1998) Drying rates generally increased with increasing temperatures and decreasing RH.

5.2.3 Quality of dried product

The higher amount of broken produced in sun drying mainly account for the uncontrolled drying and high temperature of grain due to direct exposure of grains to sun rays. During peak hours of sunshine the grain temperature in sun drying increased to higher values of 60-62 °C. Similar trends had been observed by Yamashita (1996) that when drying temperature exceeded 40℃, rice taste quality decreased. Batcher *et al*. (2004) reported that drying at elevated temperatures (71℃) caused neither marked improvement nor deterioration in the cooking quality of milled rice.

5.3 Economic analysis

Total cost of manufacturing the dryer including the cost of labour required was Rs.10850. The dryer can be used for 2400 hours annually for various grains. The profit obtained can be increased by increasing the batch capacity of the dryer and utilizing it for more number of days in the year.

SUMMARY AND CONCLUSIONS

Cereals are generally harvested at moisture content of 20-23% (w.b.) Harvesting of paddy is done at moisture content of 22%. In order to store them for longer duration without spoilage moisture removal needs to be done immediately after harvesting.

A solar powered air inflated grain dryer was developed and evaluated at Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi. The developed dryer worked on the principle of greenhouse effect in the drying chamber. Drying chamber was made up of upper transparent UV stabilized polyethylene sheet and 350 micron polyethylene sheet at the base zipped together. A DC axial fan (40 cm dia.) operating on solar power was used for inflation of drying chamber and ensured forced circulation of drying air through the provided outlet. Performance of the solar PV system (1.1×0.6×0.3 m panel size) was analyzed and found to develop average power of 58.8 W during the daytime. The power was sufficient for the air blowing unit. The developed dryer was designed for batch capacity of 100 kg of paddy grain when depth of bed was maintained at 4cm. in order to obtain the optimized operating conditions for the solar powered air inflated dryer various combinations of two different levels of thickness of upper transparent sheet (200 and 300 µm), inlet air velocities (1.5 and 3m/s) and grain bed depth (2 and 4 cm) were compared w.r.t parameters like thermal efficiency of the dryer, temperature rise in drying air and drying rate. It was found that least mean square values of thermal efficiency, temperature rise in the drying air and drying rate of the developed dryer varied from 18.7-45.7%, 3.35-5.81°C and 0.36-0.98 kg/hour respectively. Upper transparent sheet thickness (300 micron), inlet air velocity (3m/s) and grain bed depth (4cm) was found to have highest least Square mean values in the selected parameters and was selected for optimized operation of the dryer. The developed dryer performance was evaluated by drying freshly harvested paddy (PB 1121) with initial moisture content 22±0.3% (w.b.) in comparison to sun drying considering both the drying parameters and quality parameters of the dried product. The developed dryer was found to produce a significant difference in temperature of the drying air ($P < .0001$) and drying rate ($P=0.0019$) compared to sun drying. The time required for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 hours and 11-12.8 hours in sun drying respectively .The quality of dried product was analyzed in terms of milling yield and head rice yield. Milling yield of the dried paddy in the dryer didn't vary significantly (P=0.033) but the head rice yield was found to have significance difference (P <0.005) compared to sun drying. The cost of manufacturing of developed dryer was found to be Rs. 10850 and the dryer can be operated for 2400 hours throughout the year for various agricultural products/cereals etc.

The major conclusions drawn were as follows:

1. India receives tremendous amount of solar power and solar dryers can be potentially utilized for grain drying in the country.
2. Solar powered air inflated grain dryer provided faster drying along with better quality of dried paddy compared to sun drying. The dried product was also dust and contamination free compared to sunlight.
3. The dryer can be operated throughout the year depending upon the sunshine availability for various grains.
4. The low cost of construction and usage of locally available material promotes its usage as an on farm dryer.
5. The developed solar powered air inflated dryers provides a promising alternative for on farm drying of grains because of its low cost of construction, easy operation, green energy utilization and portability. The developed dryer can be used more efficiently in the rural areas where sun drying is still a major practice. Portability of the dryer enables its easy handling and carriage.

Development of Solar powered air inflated grain dryer

ABSTRACT

Cereals are generally harvested at 20-23% moisture content in order to avoid shattering losses while harvest. Their milling and long term storage is done at lower moisture content which is achieved by drying immediately after harvest. A solar powered air inflated grain dryer consists of inflated drying chamber (4.2 ×1.2 m) and a solar powered axial fan (40 cm dia.). the drying chamber was designed for drying 100 kg of paddy at bed depth of 4cm. various combinations from two different levels of upper transparent sheet thickness (200 microns and 300 microns), inlet air velocity (1.5 m/s and 3m/s) and grain bed depth (2cm and 4cm) were compared based on parameters of thermal efficiency, rise in temperature of drying air and amount of moisture removed per unit time. It was found that least square mean values of thermal efficiency, temperature rise in the drying air and drying rate of the developed dryer varied from 18.7-45.7%, 3.35-5.81°C and 0.36-0.98 kg/hour respectively. Upper transparent sheet thickness (300 micron), inlet air velocity (3m/s) and grain bed depth (4cm) was found to have highest least mean square values in the selected parameters and was selected for optimized operation of the dryer. The developed dryer performance was evaluated by drying freshly harvested paddy (PB 1121) with initial moisture content 22±0.3% (w.b.) in comparison to sun drying considering both the drying parameters and quality parameters of dried product. The developed dryer was found to produce a significant difference in temperature of the drying air (P <.0001) and drying rate (P=0.0019) compared to sun drying. The time required for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 hours and 11-12.8 hours in sun drying respectively. The quality of dried product was analyzed in terms of milling yield and head rice yield. Milling yield of the dried paddy in the dryer didn't varied significantly (P=0.033) but the head rice yield was found to have significance difference (P <0.005) compared to sun drying.

The cost of manufacturing of developed dryer was found to be Rs. 10850 and its can be operated for 2400 hours annually for various grains.

The developed solar powered air inflated dryer provides a promising alternative for on farm drying of grains because of its low cost of construction, easy operation, green energy utilization and portability.

सौर संचालित हवा द्वारा इन्फ्लेटेड अनाज ड्रायर का विकास

सार

फसल काटने के दौरान फसल को टूटने से बचाने के लिए,अनाज की कटाई आमतौर पर २०-२३ % नमी में की जाती है। उनकी मिलिंग और दीर्घकालिक भंडारण कम नमी पर किया जाता है जो फसल के कटाई के तुरंत बाद सुखाकर हासिल किया जाता है। एक सौर संचालित वायु इंफ्लेटेड अनाज ड्रायर में इन्फ्लेटेड सुखाने का कक्ष (४.२ × १.२ मीटर) और एक सौर संचालित अक्षीय प्रशंसक (४० से. मि डाया) होता है। सुखाने के कक्ष को ४ सेंटीमीटर की सतह गहराई पर १०० किलोग्राम धान सूखने के लिए डिजाइन किया गया। शीर्ष पारदर्शी शीट की मोटाई (२०० माइक्रोन और ३०० माइक्रोन) के दो अलग-अलग स्तरों से विभिन्न संयोजन, इनलेट वायु वेग (१.५ मीटर / सेकंड और ३ मीटर / सेकंड) और अनाज सतह की गहराई (२ सेंटीमीटर और ४ सेंटीमीटर) की तुलना विभिन्न मानकों के आधार पर की गई थी जैसे, थर्मल दक्षता ,हवा के तापमान में वृद्धि और प्रति यूनिट समय में नमी की मात्रा हटाने की समता। यह पाया गया कि थर्मल दक्षता के कम से कम वर्ग औसत मूल्य, सुखाने वाली हवा में तापमान वृद्धि और विकसित ड्रायर की सुखाने की दर क्रमशः १८.७ -४५.७ %, ३.३५ -५.८१ डिग्री सेल्सियस और ०.३६-०.९८ किलोग्राम / घंटा से भिन्न है। शीर्ष पारदर्शी शीट मोटाई (३०० माइक्रोन), इनलेट वायु वेग (३ मीटर / सेकंड) और अनाज बिस्तर गहराई (४ सेंटीमीटर) चयनित पैरामीटर में कम से कम औसत वर्ग मान पाए गए थे और ड्रायर के अनुकूलित संचालन के लिए चुना गया था। सूखे उत्पाद के सुखाने वाले पैरामीटर और गुणवत्ता मानकों दोनों पर विचार करते हुए सूर्य सुखाने की तुलना में प्रारंभिक नमी सामग्री २२ ± ०.३ % (वेट बेसिस) के साथ ताजा कटाई वाले धान (पीबी ११२१) के साथ विकसित ड्रायर प्रदर्शन का मूल्यांकन किया गया । विकसित ड्रायर सुखाने की हवा (पी <.०००१) के तापमान और सुखाने की दर (पी =०.००१९) के तापमान में सूर्य सूखने की तुलना में एक महत्वपूर्ण अंतर पैदा करने के लिए पाया गया था। विकसित ड्रायर में १४% की नमी सामग्री को मिलाकर धान की सूखने के लिए आवश्यक समय क्रमशः सूर्य सुखाने में ७.५ -९ घंटे और ११ -१२.८ घंटे तक था। सूखे उत्पाद की गुणवत्ता का उत्पादन मिलिंग उपज और हेड राइस यील्ड के मामले में किया गया था। ड्रायर में सूखे धान की मिलिंग उपज में काफी भिन्नता नहीं थी (पी = ०.०३३) लेकिन हेड राइस यील्ड सन डॉयिंग की तुलना में महत्व अंतर (पी <०.००५) पाया गया था।

विकसित ड्रायर के निर्माण की लागत १०५५० थी । प्रतिवर्ष ड्रायर का उपयोग २४०० घंटो के लिए विभिन्न अनाजों के लिए किया जा सकता है।

विकसित सौर संचालित हवा इन्फ्लेटेड दरयरस के निर्माण की कम लागत, आसान संचालन, हरी ऊर्जा का उपयोग और पोर्टेबिलिटी के कारण अनाज को खेत में सुखाने के लिए एक आशाजनक विकल्प प्रदान करता है।

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APPENDIX-I

Mean solar insolation on surface of PV panel (tilt) at various times during the experiments in month of February and March

Time	Mean solar insolation (W/m²) Mean ± (S.D)
9:30 AM	526. ±66.89
10:00 AM	550±74.11
10:30 AM	582±81.14
11:00 AM	621±78.98
11:30 AM	653±82.00
12:00 PM	676±79.61
12:30 PM	696±79.61
1:00 PM	720±70.8
1:30 PM	698±59.0
2:00 PM	675±69.8
2:30 PM	652±68.1
3:00 PM	619±86.1
3:30 PM	593±76.5
4:00 PM	545±69.90
4:30 PM	502±71.3
5:00 PM	460±74.79
9:30 AM	530±57.21
10:00 AM	552±57.85
10:30 AM	577±63.63
11:00 AM	599±77.25
11:30 AM	640±71.69
12:00 PM	667±73.1
12:30 PM	703±73.64
1:00 PM	707±71.6

APPENDIX-II

Mean Current and voltage produced by the solar PV panel during the experimental days

TIME	CURRENT(A) (Mean± S.D.)	VOLTAGE(V) (Mean± S.D.)
9:30 AM	3.14±0.40	16.01±0.47
10:00 AM	3.24±0.43	16.23±0.48
10:30 AM	3.38±0.35	16.40±0.55
11:00 AM	3.59±0.33	16.60±0.53
11:30 AM	3.74±0.35	16.74±0.55
12:00 PM	3.82±0.42	16.83±0.56
12:30 PM	3.89±0.32	16.95±0.690
1:00 PM	4.01±0.32	17.15±0.53
1:30 PM	3.91±0.36	16.97±0.52
2:00 PM	3.83±0.37	16.96±0.47
2:30 PM	3.69±0.45	16.63±0.63
3:00 PM	3.58±0.41	16.43±0.54
3:30 PM	3.48±0.39	16.35±0.48
4:00 PM	3.26±0.35	16.12±0.80
4:30 PM	3.03±0.36	15.80±1.01
5:00 PM	2.86±0.34	15.38±0.45
9:30 AM	3.16±0.32	16.08±0.42
10:00 AM	3.31±0.36	16.28±0.41
10:30 AM	3.43±0.40	16.67±0.61
11:00 AM	3.52±0.34	16.83±0.49
11:30 AM	3.65±0.35	16.67±0.56
12:00 PM	3.81±0.36	16.87±0.60
12:30 PM	3.92±0.36	17.08±0.56
1:00 PM	3.94±0.34	17.02±0.47

APPENDIX-III

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (300 microns), Inlet air velocity (1.5 m/s) and grain bed depth (2cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	25.2	25.9	30.9	29.4	40.8	40.9	43.3	47.7
10:00 AM	25.8	28.3	33.7	32.4	40.2	39.7	43.9	49.7
10:30 AM	26	28	33.7	32.9	40.0	39.2	44.5	50.5
11:00 AM	27	28.8	34.5	32.5	38.4	36.4	42.2	49.1
11:30 AM	27.9	30.0	36.1	35.3	36.5	36.1	40.9	48.3
12:00 PM	28.4	29.8	36.7	35.5	34.9	34.2	38.6	46.6
12:30 PM	29.2	31.7	39.0	37.2	33.7	32.5	37.2	47.9
1:00 PM	29.9	32.3	37.8	35.8	32.1	31.5	39.2	48.2
1:30 PM	30.9	31.6	38.6	36.3	30.2	29.8	35.9	46.7
2:00 PM	31.3	34.1	41.2	38.3	29.3	28.1	33.8	43.6
2:30 PM	30.7	32.5	38.8	37.3	28.8	27.8	32.8	42.0
3:00 PM	30.3	31.2	37.2	35.6	28.5	27.1	31.2	40.1
3:30 PM	28	30.1	35.7	33.1	28.7	28.1	33.1	42.0
4:00 PM	27.0	29.3	34.5	32.1	30.4	29.4	33.1	42.3
4:30 PM	26.7	28.4	33.4	31.2	31.4	30.2	34.2	39.8
5:00 PM	25.8	26.9	30.9	29.4	34.8	33.0	36.2	40.4
9:30 AM	26.3	27.8	32.0	30.5	40	39.2	41.5	46.1
10:00 AM	26.6	28.2	33.2	31.7	38.7	37.6	41.5	46.6
10:30 AM	27.3	28.7	33.9	32.1	37.6	35	38.4	45.3
11:00 AM	28.1	29.6	35.3	33.2	35.7	33.8	38.3	47.2
11:30 AM	28.7	30.0	36.0	33.8	33.9	31.0	35.2	44
12:00 PM	29.8	31.7	38.0	35.8	32.2	29.8	35.7	45.1
12:30 PM	30.5	32.2	37.7	35.5	30.5	30.1	35.8	47.9
1:00 PM	25.2	25.9	30.9	29.4	40.8	40.9	43.3	47.7

APPENDIX- IV

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (300 microns), Inlet air velocity (3 m/s) and grain bed depth (2cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	25.8	28.0	31.8	33.16	42.2	35.7	40.0	47.2
10:00 AM	27.1	29.0	35.8	34.4	41.2	35.6	40.4	46.5
10:30 AM	27.8	30.4	36.2	34.56	40.4	33.8	39.7	47.1
11:00 AM	29.3	31	37	35.1	38.1	32.6	38.8	47.2
11:30 AM	30.1	32.9	39.7	37.1	37.8	32.7	39.8	48.5
12:00 PM	31.7	33.3	43.2	40.5	36.2	30.9	41.1	51.0
12:30 PM	32	34.7	42.9	39.6	35.3	29.6	37.6	48
1:00 PM	32.9	34.8	44.7	41.7	33.9	30.2	38.1	48.7
1:30 PM	33.0	36.5	44.4	41.2	32.3	29.5	38.03	47.3
2:00 PM	32.7	35.0	42.3	40.6	30.8	31.3	37.3	47.0
2:30 PM	31.6	32.8	41.3	38.6	29.5	28.4	36.3	50.0
3:00 PM	31.4	32.7	41.1	39.0	29.9	27.23	35.27	48.2
3:30 PM	31.3	33.9	40.8	38.7	29.1	29.3	34.8	45.9
4:00 PM	29.8	29.9	37.4	35.5	28.2	25.9	32.8	46.3
4:30 PM	27.7	29.0	32.4	30.8	31.4	28.2	31.5	42.1
5:00 PM	26.7	26.7	31.3	29.1	33.1	28.3	32.9	38.8
9:30 AM	25.8	26.8	30.3	28.5	42.2	36.8	37.3	47.3
10:00 AM	27.0	27.3	33.4	31.5	40.9	36	42.1	49.6
10:30 AM	27.3	28.9	35.7	33.2	38.6	33.6	41.4	46.1
11:00 AM	28.9	28.9	36.4	33.5	37.9	33.6	40.1	46.3
11:30 AM	30.3	31.8	39.5	37.2	36.1	33.1	40.1	48.2
12:00 PM	31.6	33	41.0	36.6	35.9	32.6	38.7	49.3
12:30 PM	32.4	35.1	41.9	34.9	33.8	31.9	36.7	42.8
1:00 PM	32.9	34.5	43.1	36.1	31.7	30.5	35.6	44.4

APPENDIX-V

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (300 microns), Inlet air velocity (1.5 m/s) and grain bed depth (4cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
25.0	26.6	31.0	29.2	41.1	39.6	44.8	53.0	25.0
25.7	25.8	32.2	30.8	39.5	38.5	43.8	53.9	25.7
27.0	29.5	34.7	33.6	39.7	38.7	43.7	54.7	27.0
27.4	28.4	36.2	33.8	37.1	36.3	40.6	52.7	27.4
28.5	31.1	37.6	35.3	35.4	33.2	39.3	53.5	28.5
30.2	31.6	40	37.8	33.5	32.4	36.4	52.7	30.2
30.3	32.9	40.9	39.3	32.2	30.3	36.8	50.3	30.3
30.5	32.0	40.4	38.4	30.5	29.6	35.7	48.9	30.5
30.8	33.4	41.5	39.9	29.4	28.5	36	51.6	30.8
31	31.8	41.3	39.7	29.4	27.9	34.9	51.9	31
29.5	31.6	40.6	39.0	27.7	25.5	32.6	53.0	29.5
29.0	30.3	35.5	33.9	28.7	27.7	33.1	49.4	29.0
27.9	29.9	34.9	33.7	31.2	27.9	34.9	50.9	27.9
27.1	27.7	34.2	33.5	32.0	30.5	37.2	53.0	27.1
25.7	26.8	34.2	32.7	33.8	32.0	38.8	53.9	25.7
25.5	25.5	31.7	30.3	37.7	35.6	39.9	47.55	25.5
25.4	27.0	31.0	28.8	42.3	39.6	43.8	49.8	25.4
26.3	27.3	32.4	30.8	40.9	38.3	43.9	51.5	26.3
27	29.8	36	33.8	37.4	35	37.9	45.9	27
28.5	29.8	38.7	36.7	37.4	34.5	37.9	48	28.5
29.2	32.3	39.8	37.5	39.8	36	43.5	52.9	29.2
29.9	31.5	39.1	36.0	37.8	36	45	54	29.9
31.3	33.2	40.8	38.2	37	36	44	55.2	31.3
34	36	43.8	41.5	35.5	36	44.2	56.2	34

APPENDIX-VI

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (200 microns), Inlet air velocity (1.5 m/s) and grain bed depth (4cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	25.4	26.9	30.8	28.4	40.0	37.2	42.1	49.5
10:00 AM	26.0	27.4	33.4	31.9	38.8	36.3	42.4	50.4
10:30 AM	26.8	28.8	34.8	32.9	38.0	36.0	42.9	59.6
11:00 AM	27.8	28.9	35.7	34.2	36.1	34.1	40.3	51.1
11:30 AM	28.4	30.7	37.2	35.1	33.4	33.4	39.4	50.4
12:00 PM	29.5	31.6	39.3	37.4	31.5	29.3	35.9	51.4
12:30 PM	30.3	32.8	39.3	37.5	29.6	28.0	34.4	46.4
1:00 PM	31.0	32.9	39.9	38.0	28.2	26.7	32.9	44.9
1:30 PM	31.3	33.3	39.3	37.5	27.5	26.2	33.2	43.2
2:00 PM	30.7	32.1	38.6	36.3	26	24	31	41.9
2:30 PM	31	32	38.9	36.3	26.1	23.8	29.3	37.3
3:00 PM	29.3	30.1	37.0	34.9	26.5	25.0	31.0	38.5
3:30 PM	27.5	28.9	33.1	31.2	28.1	26.4	31.1	38.1
4:00 PM	26.1	27.4	33.2	31.2	29.4	26.6	28.4	33.8
4:30 PM	25.6	27	30.2	29.2	32	30.3	33.2	35.2
5:00 PM	26.25	26.6	30.6	28.5	37	35.1	39	45.2
9:30 AM	26.3	27.7	31.4	29.1	40.2	38.2	42.7	50.2
10:00 AM	26.8	27.9	32.7	30.5	38.9	36.7	42.5	50.8
10:30 AM	27.5	30.2	34.7	32.6	37.0	35.1	41.7	51.6
11:00 AM	27.9	29.8	35.8	33.6	35.8	34.1	42.0	53.6
11:30 AM	29.2	32.0	37.6	35.3	34.0	32.2	41.1	51.1
12:00 PM	30.3	32.4	39.0	36.8	31.9	30.6	38.9	49.4
12:30 PM	31.5	34.2	40.8	38.4	30.3	30.3	38.4	50.1
1:00 PM	31.5	34	41	38.6	35.5	36	44.2	56.2

APPENDIX-VII

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (200 microns), Inlet air velocity (3 m/s) and grain bed depth (4 cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	26.5	28.4	31.4	29.8	40.1	40.7	45.8	53.4
10:00 AM	27.2	27.8	32.7	30.7	39.3	40.5	46.6	55.5
10:30 AM	27.6	29.6	32.7	30.7	38.6	39.4	47.4	56.6
11:00 AM	28.3	29.2	33.7	32.9	36.0	38.1	46.6	55.8
11:30 AM	29.2	31.4	36.3	34.4	32.6	34.0	43.5	53.1
12:00 PM	30.2	31.6	37.1	35.2	31.3	32.9	44.4	56.2
12:30 PM	30.3	32.8	37.5	34.9	30.9	33.3	44.7	58.2
1:00 PM	31.1	32.0	37.2	34.4	28.9	31.1	41.7	55.0
1:30 PM	31.9	34.0	37.8	36.4	27.6	30.0	41.3	50.4
2:00 PM	31.3	32.1	39.1	36.8	27.3	29.9	42.4	53.8
2:30 PM	30.3	33.0	38.1	36.7	27.1	29.2	37.6	40.4
3:00 PM	29.7	30.6	37.8	35.2	28.4	30.8	37.6	45.2
3:30 PM	27.3	29.6	34.6	32.6	29.5	31.0	37.1	44.9
4:00 PM	26.1	28.4	31.7	29.9	30.4	32.6	37.1	43.9
4:30 PM	25.3	26.6	29.5	29.6	32.0	31.7	36.9	42.5
5:00 PM	25.2	27.1	28.9	29.2	31.7	33.7	39.1	43.8
9:30 AM	26.4	27.7	30.8	29.6	40.1	41.2	45.3	54.0
10:00 AM	25.8	27.3	31.7	29.5	38.6	40.2	44.6	53.2
10:30 AM	26.1	27.9	32.6	31.1	38.1	39.4	45.6	54.5
11:00 AM	26.5	28.0	33.3	30.9	36.2	37.4	43.6	52.4
11:30 AM	27.7	29.3	34.6	32.2	33.6	34.6	40.4	47.8
12:00 PM	28.1	29.8	35.8	33.9	30.9	32.5	39.1	48.8
12:30 PM	28.7	31.1	37.2	35.2	28.6	30.1	37.0	47.3
1:00 PM	28.6	31.0	37.0	34.6	34.0	32.1	38.0	49.0

APPENDIX-VIII

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (300 microns), Inlet air velocity (3 m/s) and grain bed depth (4 cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	26.1	28.1	32.7	31.9	39.4	38.3	43.2	48.0
10:00 AM	27.8	27.8	34.9	36.6	38.6	37.2	42.5	50.4
10:30 AM	28.7	31.3	37.2	36.6	39.7	38.3	43.3	54.1
11:00 AM	29.5	29.6	38.0	37.6	37.0	36.2	43.5	54.7
11:30 AM	30.4	32.2	39.8	37.6	36.1	36.3	44.7	56.4
12:00 PM	31.6	32.4	41.4	39.7	34.3	32.1	40.8	52.9
12:30 PM	32.1	34.1	41.3	39.7	33.8	31.2	38.8	52.4
1:00 PM	32.4	32.4	41.4	38.7	31.8	30.1	39.0	52.0
1:30 PM	32.5	34.8	41.2	38.7	31.0	29.0	37.2	49.7
2:00 PM	32.3	32.4	41.1	37.6	29.7	27.6	36.2	46.9
2:30 PM	31.2	33.5	38.8	37.6	29.2	28.1	34.5	44.5
3:00 PM	30.5	30.3	38.6	35.4	27.7	25.9	32.8	43.1
3:30 PM	29.3	32.1	37.0	35.4	29.1	27.7	32.0	41.4
4:00 PM	27.1	27.6	34.9	30.7	31.0	29.4	31.7	36.1
4:30 PM	26.0	28.4	32.5	30.7	32.1	30.1	32.4	37.4
5:00 PM	24.9	24.7	31.4	30.3	33.3	31.9	33.7	38.4
9:30 AM	25.6	27.5	31.8	30.3	39.7	37.9	42.0	46.2
10:00 AM	26.8	27.1	33.2	32.8	38.5	37.1	41.3	48.0
10:30 AM	27.8	29.6	34.4	32.8	39.1	38.6	43.8	53.2
11:00 AM	29.4	29.8	36.6	35.8	38.0	36.8	45.1	54.3
11:30 AM	29.6	32.0	37.8	35.8	35.9	35.3	43.2	52.3
12:00 PM	31.1	31.1	39.6	39.4	35.4	34.4	42.7	50.9
12:30 PM	31.7	33.7	41.3	39.4	34.1	32.6	41.9	50.2
1:00 PM	33.0	35.0	41.1	39.0	33.0	31.9	40.2	52.0

APPENDIX-IX

Temperature and relative humidity of ambient and drying air for upper transparent sheet thickness (200 microns), Inlet air velocity (3 m/s) and grain bed depth (2cm)

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	26.3	27.2	31.7	31.3	38.4	37.0	41.4	49.0
10:00 AM	27.1	27.8	32.5	32.6	38.5	36.7	41.3	49.3
10:30 AM	28.0	29.9	33.1	34.8	37.5	36.2	42.2	49.4
11:00 AM	28.6	29.3	33.0	34.3	36.5	35.8	41.7	50.3
11:30 AM	30.1	30.8	33.4	35.6	35.1	34.7	38.2	47.1
12:00 PM	30.3	29.7	33.0	33.9	32.8	33.4	36.1	48.0
12:30 PM	31.8	31.8	34.3	38.6	32.3	32.2	36.6	47.2
1:00 PM	32.2	33.2	35.9	40.5	31.2	30.2	38.4	46.2
1:30 PM	32.0	33.0	35.6	40.7	30.2	28.5	39.3	46.4
2:00 PM	32.7	33.9	36.8	41.5	29.0	27.4	38.1	49.3
2:30 PM	31.2	32.6	34.5	39.9	28.1	26.9	38.8	50.2
3:00 PM	31.2	32.2	32.9	35.2	28.9	28.0	38.9	49.4
3:30 PM	28.9	30.2	32.3	35.3	31.4	29.2	40.5	47.2
4:00 PM	27.4	28.5	30.2	29.9	33.4	31.7	40.3	47.0
4:30 PM	27.0	27.7	31.7	31.0	34.9	33.7	39.7	45.9
5:00 PM	25.8	25.3	31.9	33.1	39.7	39.3	43.2	46.6
9:30 AM	26.1	27.0	31.7	30.9	40.1	40.1	45.2	50.0
10:00 AM	27.6	28.4	33.4	32.8	41.1	39.6	45.3	52.7
10:30 AM	28.1	29.3	33.2	34.0	38.6	37.3	43.6	51.3
11:00 AM	28.8	29.9	33.5	34.0	36.7	35.4	43.8	53.0
11:30 AM	30.5	32.5	34.7	34.9	34.8	33.9	40.8	51.5
12:00 PM	31.3	32.7	34.1	36.4	33.6	32.4	40.9	49.4
12:30 PM	31.3	33.3	35.5	38.6	32.2	31.5	40.1	49.3
1:00 PM	32.1	33.2	39.9	38.2	33.0	31.6	38.9	49.9

APPENDIX-X

Time	Ambient Temp. (°C)	Temp. at 1m from inlet) (°C)	Temp. at 2.5 m from inlet) (°C)	Temp. at 4 m from inlet) (°C)	Ambient RH (%)	RH at 1m from inlet (%)	RH at 2.5 m from inlet (%)	RH at 4m from inlet (%)
9:30 AM	26.6	27.9	32.0	32.1	36.8	31.3	31.3	31.33
10:00 AM	27.4	28.3	34.1	34.8	36.1	32.6	32.6	32.6
10:30 AM	28.2	30.3	35.4	34.5	35.1	34.8	34.8	34.8
11:00 AM	28.9	29.9	36.7	35.9	35.9	34.2	34.2	34.2
11:30 AM	29.9	32.8	38.8	37.2	33.7	35.5	35.5	35.5
12:00 PM	30.7	32.3	41.0	38.9	32.9	33.9	33.9	33.9
12:30 PM	31.1	33.8	41.2	38.4	31.4	38.6	38.6	38.6
1:00 PM	31.6	33.4	42.1	39.6	28.7	40.5	40.5	40.5
1:30 PM	32.1	35.6	42.3	40.1	27.3	40.6	40.6	40.6
2:00 PM	32.3	34.5	41.4	40.0	26.0	41.5	41.5	41.5
2:30 PM	32.1	34.2	40.4	38.4	25.1	39.9	39.9	39.9
3:00 PM	31.0	32.6	41.5	39.4	25.8	35.2	35.2	35.2
3:30 PM	30.6	34.1	40.0	38.5	27	35.3	35.3	35.3
4:00 PM	29.1	30.3	36.4	35.0	29.0	29.9	29.9	29.9
4:30 PM	27.4	29.9	33.3	32.2	29.9	30.9	30.9	30.9
5:00 PM	26.3	26.8	32.5	31.7	32.3	33.1	33.1	33.1
9:30 AM	25.8	27.5	30.7	29.5	35.4	30.9	30.9	30.9
10:00 AM	26.7	27.4	32.9	31.7	38.0	32.8	32.8	32.8
10:30 AM	27.6	29.2	34.6	33.0	36.8	34.0	34	34
11:00 AM	28.2	28.8	35.7	33.6	35.7	34.0	34.0	34.0
11:30 AM	28.0	30.6	36.9	34.6	33.6	34.9	34.9	34.9
12:00 PM	29.6	31.5	38.8	35.7	35.1	36.3	36.3	36.3
12:30 PM	30.2	33.1	39.7	34.5	34.3	38.6	38.6	38.6
1:00 PM	30.5	33.2	40.7	34.2	35.5	38.2	38.2	38.2

APPENDIX-XI

Buck Converter (Step-Down Converter) specifications

Input Voltage	6-24V
Output Voltage	5V
Maximum Output Current	3A
Conversion Efficiency	97.5%
Dimensions	25mm X 15mm X 8mm
Weight	6 g
Full load temperature	30^0C
Static Current	0.85mA
Operating temperature	-40^0C to $+85^0$C
Load regulation	±1%
Voltage Regulation	±0.5%
Switch frequency	500KHz

Specifications of Micro-SD card module

Item	Minimum	Typical	Maximum	Unit
Power Voltage VCC	4.5	5	5.5	V
Current	0.2	80	200	Ma
Interface Electrical Potential		3.3 or 5		V
Support Card Type	Micro SD Card (<=2GB) Micro SDHC Card (<=32GB)			
Size	42×24×12			mm
Weight	5			g

Specifications of liquid crystal display

Item	Standard Value	Unit
Module Dimensions	146.0×62.5	Mm
Viewing Area	123.5×43.0	
Dot Size	0.92×1.10	
Dot Pitch	0.98×1.16	
Mounting Hole	139.0×55.5	
Character Size	4.48×9.22	

Specifications of Aurduino Uno

Microcontroller	ATmega328
Operating Voltage	5 V
Input Voltage (recommended):	7-12 V
Digital I/O Pins	14
DC Current per I/O Pin	40 Ma
Flash Memory	32 KB

Specifications of DHT 11 sensor

Operating Voltage	3.5V to 5.5V
Operating current	0.3 Ma
Output	Serial data
Temperature Range	0°C to 50°C
Humidity Range	20% to 90%
Resolution	Temperature and Humidity both are 16-bit
Accuracy	±1°C and ±1%

Appendix XII

Moisture content and amount of moisture removed per unit time interval in the developed dryer and sun drying.

Time	Moisture content (%) in developed dryer	Amount of moisture removed in given interval (kg/h)	Moisture content (%) in sun drying	Amount of moisture removed in given interval (kg/h)
9:30 AM	22.04	0	22.04	0
10:00 AM	21.656	0.768	21.714	0.652
10:30 AM	21.244	0.824	21.358	0.712
11:00 AM	20.802	0.884	21.002	0.712
11:30 AM	20.34	0.924	20.587	0.83
12:00 PM	19.85	0.98	20.142	0.89
12:30 PM	19.28	1.14	19.69	0.904
1:00 PM	18.69	1.18	19.215	0.95
1:30 PM	18.08	1.22	18.77	0.89
2:00 PM	17.46	1.24	18.344	0.852
2:30 PM	16.91	1.1	17.88	0.928
3:00 PM	16.4	1.02	17.46	0.84
3:30 PM	15.91	0.98	17.01	0.9
4:00 PM	15.45	0.92	16.69	0.64
4:30 PM	15.09	0.72	16.331	0.718
5:00 PM	14.73	0.72	16.02	0.622
9:30 AM	15.2	0	16.9	0
10:00 AM	14.95	0.5	16.544	0.712
10:30 AM	14.51	0.88	16.17	0.748
11:00 AM	14.05	0.92	15.75	0.84
11:30 AM	-	-	15.41	0.68
12:00 PM	-	-	14.77	1.28
12:30 PM	-	-	14.37	0.8
1:00 PM	-	-	14	0.74

Appendix XIII

Average temperature of drying air in the developed dryer and sun drying

Average drying air Temp. ((°C) Solar powered air inflated grain dryer	Drying air Temp. at Sun drying (°C)
29.8	26.3
30.2	27.1
30.2	27.1
30.6	28.4
33	29.5
36.8	30.6
37.53	31.8
38.2	33.9
36.6	34.5
35.63	34.7
38.3	32.3
36.73	34
33.7	31.7
31.5	30
30.56	29.8
29.23	27
30.0	25.8
31.2	27.2
31.2	28.4
31.7	30

Appendix XIV

Program of the developed data logger for measurement of temperature and relative humidity using Aurduino mega

```
#include <DS1302.h>
DS1302 rtc(2, 3, 4);
#include <DHT.h>

#include "DHT.h"
#include <SPI.h>  //SD card library
#include <LiquidCrystal.h>  //display library
#include <SD.h> //SD card library
File myFile;
#define DHTPIN1 A0     // what pin we're connected to
#define DHTPIN2 A1
#define DHTPIN3 A2
#define DHTTYPE1 DHT11   // we are using the DHT11 sensor
#define DHTTYPE2 DHT11
#define DHTTYPE3 DHT11
DHT dht1(DHTPIN1, DHTTYPE1);
DHT dht2(DHTPIN2, DHTTYPE2);
DHT dht3(DHTPIN3, DHTTYPE3);
 const int rs = 27, en = 26, d4 = 25, d5 = 24, d6 = 23, d7 = 22;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

void setup()
{
  // Set the clock to run-mode, and disable the write protection
  rtc.halt(false);
  rtc.writeProtect(false);

  // Setup Serial connection
  Serial.begin(9600);

  // The following lines can be commented out to use the values already stored in the
DS1302
  //rtc.setDOW(MONDAY);        // Set Day-of-Week to FRIDAY
  //rtc.setTime(12, 27, 0);     // Set the time to 12:00:00 (24hr format)
  //rtc.setDate(15, 2, 2018);   // Set the date to August 6th, 2010
dht1.begin();
dht2.begin();
dht3.begin();
lcd.begin(16,2);
lcd.clear();
//sd card reader programm start*****************************************
 while (!Serial) {
    ; // wait for serial port to connect. Needed for native USB port only
  }
```

```
  Serial.print("Initializing SD card...");

  if (!SD.begin(53)) {
    Serial.println("initialization failed!");
    while (1);
  }
  Serial.println("initialization done.");

  // open the file. note that only one file can be open at a time,
  // so you have to close this one before opening another.
  myFile = SD.open("test.csv", FILE_WRITE);

  // if the file opened okay, write to it:
  if (myFile) {
    Serial.print("Writing to test.csv...");
    myFile.println("New Test Readings");
    myFile.println("Date, Time, Temp1 Degree C, RH1 %, Temp2 Degree C, RH2 %,
Temp3 Degree C, RH3 %");
    // close the file:
    myFile.close();
    Serial.println("done.");
  } else {
    // if the file didn't open, print an error:
    Serial.println("error opening test.csv");
  }

  /* re-open the file for reading:
    myFile = SD.open("test.csv");
  if (myFile) {
    Serial.println("test.csv:");

    // read from the file until there's nothing else in it:
    while (myFile.available()) {
      Serial.write(myFile.read());
    }
    // close the file:
    myFile.close();
  } else {
    // if the file didn't open, print an error:
    Serial.println("error opening test.csv");
  }*/
  //sd card adapter programm close***************************************
}

void loop()
{
  // Send Day-of-Week
  Serial.print(rtc.getDOWStr());
```

```
 Serial.print(" ");

 // Send date
 Serial.print(rtc.getDateStr());
 Serial.print(" -- ");

 // Send time
 Serial.println(rtc.getTimeStr());
 float h1 = dht1.readHumidity();
 int t1 = dht1.readTemperature();  // Read temperature as Celsius (the default)
 float h22 = dht2.readHumidity();
 int t2 = dht2.readTemperature();
 float h33 = dht3.readHumidity();
 int t3 = dht3.readTemperature();
 //float h1 = 0.7784*h11+10.378;
 float h2 = 0.5627*h22+32.367;
 float h3 = 0.8942*h33-12.032;
 //float h3 = 0.0682* pow(h33,1.5578);
 Serial.print("temp1 = ");
 Serial.print(t1);
 Serial.print("\t RH1%=");
 Serial.print(h1);
 Serial.print("\t temp2 = ");
 Serial.print(t2);
 Serial.print("\t RH2%=");
 Serial.print(h2);
 lcd.setCursor(0,0);
   lcd.print("TEMP:");
   lcd.print(t2);
   lcd.print(" ");
   lcd.print(rtc.getTimeStr());
   lcd.setCursor(0,1);
   lcd.print("RH:");
   lcd.print(h2);
   lcd.print("%");
 Serial.print("\t temp3 = ");
 Serial.print(t3);
 Serial.print("\t RH3%=");
 Serial.println(h3);
 myFile = SD.open("test.csv", FILE_WRITE);
 myFile.print(rtc.getDateStr());
 myFile.print(", ");
 myFile.print(rtc.getTimeStr());
 myFile.print(", ");
 myFile.print(t1);
 myFile.print(", ");
myFile.print(h1);
 myFile.print(", ");
 myFile.print(t2);
 myFile.print(", ");
```

```
  myFile.print(h2);
  myFile.print(", ");
  myFile.print(t3);
  myFile.print(", ");
  myFile.print(h3);
  myFile.print("\n");
  myFile.close();
  delay(300000);
}
```