सब्जी बीज के लिए स्वचालित सौर ड्रायर का विकास

DEVELOPMENT OF AUTOMATED SOLAR DRYER FOR VEGETABLE SEEDS

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DEVELOPMENT OF AUTOMATED SOLAR DRYER FOR VEGETABLE SEEDS

A Thesis

By

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This is to certify that the thesis entitled, **"DEVELOPMENT OF AUTOMATED SOLAR DRYER FOR VEGETABLE SEEDS"** submitted to the Faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY IN AGRICULTURAL ENGINEERING** is a record of *bona fide* research work carried out by **Ms. THINGUJAM BIDYALAKSHMI DEVI, Roll No. 10382** under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma. It is further certified that all the assistance and help availed during the course of investigation as well as all sources of information have been duly acknowledged by her.

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Dedicated To

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Chapter 1

INTRODUCTION

Vegetables are well known for its nutraceutical properties as they supplement rare minerals, vitamins, fibre and other micronutrients. They play a vital role in providing not only food security but also nutritional security. India ranks second in the production of fruits and vegetables next to China. The production of vegetables in India is 1.7x 10^8 tons from an area of 9.5x 10^6 hectare in 2014-15 (Anonymous, 2016). Out of these popular vegetables, commonly consumed and available throughout the country and round the year are onion, carrot and tomato. Onions are mostly consumed for its unique flavor and it has high content of polyphenolic flavonoids (Randle, 1997). Carrots are good source of vitamin A which has high antioxidant properties (Rao *et al.*, 1999). Tomatoes are rich in lycopene, vitamin C and vitamin E (Sanchez-Moreno *et al.*, 2006). Due to improve economical and living standard, and knowledge on nutritional benefits of vegetables resulted in increased demand. Because of increase in knowledge on its nutritional benefits, there is increased in demand of vegetables. The productivity of vegetables in India is half of the productivity of USA and many other developed countries. It is necessary to increase the productivity to fulfil the increasing population demand. To enhance productivity, quality seed is must.

It has been observed in multi-location coordinated trials under National Seed Project that about 20-30 % average increase in productivity could be achieved with the use of quality seed (Chowdhary, 2004). Use of quality seed also effects extensively on other input (irrigation, fertilizer, pesticides etc.) use efficiency (Rashid and Singh, 2000). It also supports in improving the economic viability of vegetable seed production system. Main parameters for seed quality measurements are germination, vigor, viability, seed health and electrical conductivity (Ertsey, 2009).

Seed processing is of paramount importance for maintaining quality. The important unit operation in seed processing are extraction, cleaning, grading, washing, drying and storage. High moisture content is the main reason for deterioration of seeds due to mould and insect attack, and high respiration during storage. These result in loss of seed quality. Seed are usually harvested at physiological maturity having moisture content of about 16-18% wet basis. Therefore, it is necessary to reduce the moisture content of seeds to a safe level for storage. Seeds at 18 to 20%, moisture content increased respiration resulting in rapid deterioration of the seed. As suggested by Harrington (1960), 1% increase in moisture content from safe limit can double the decline of germination rate. Temperature and moisture content are the important factors affecting seed quality during storage. Both have positive correlation. High moisture content results in increase of respiration rate and hence increase in temperature and vice-versa. Therefore, it is necessary to reduce moisture content before storage through proper drying process.

Drying is one of the most important and sensitive unit operations in seed processing to reduce the moisture content to a safe level for storage. There are different methods for seed drying depending upon the species, initial moisture content and resources available. Hot air, sun, shade, vacuum, freeze and refrigeration drying are most common types of drying method (Ellis and Roberts, 1980). However, commonly used method is sun drying which results into poor quality of the seed due to uncontrolled weather conditions. Wise handling and care is necessary during drying to maintain its quality and to prevent seed injury. Seed quality may loss in slow drying due to ageing whereas fast drying may result in desiccation damage. Therefore, Selection of proper temperature for drying is necessary. It was observed that there were no injuries on corn seed when dried at 35ºC but lost its viability at 50ºC (Herter and Burris, 1989). Optimum drying temperature in terms of drying time and seed quality was obtained at 42 ºC (Hossain *et al.*, 2015). For drying vegetable seeds, it is advisable to use drying air temperature less than 35 ºC (Hunje *et al.*, 2007). Hence, it is important to design efficient dryer to dry the seeds without losing its quality.

To design and select an efficient dryer, it is necessary to study engineering properties of the crop and its drying behaviour. In fact, designing the seed processing equipment without considering engineering properties of biomaterials may yield poor results (Davies and El Okene, 2009). Engineering properties of biological materials include physical, mechanical, aerodynamics, thermal and optical properties. Moisture content affects the engineering properties of the crop seeds. Bulk density, true density, porosity and coefficient of friction on five different surfaces of Corchorus olitorius decreased within the studied moisture range of 9.86 % db and 17.69 % db. The relationship between the properties and moisture content was expressed by the regression model (Ilori and Akinyele, 2016). The engineering properties of vegetable seeds which are small and delicate are different from cereals crop. Due to delicacy of vegetable seeds and also being a costly input, accurate knowledge of its engineering properties is very necessary for the design of the dryer. Information on engineering properties of these vegetables are very less.

Proper drying process of seed needs knowledge of its drying kinetics. Mathematical modelling and simulation of drying curves help in study of drying variables and to optimize drying parameters and conditions (Fernando and Amarasinghe, 2016). Most commonly used thin-layer drying models are Newton, Khazaei, Peleg, Page, Modified page, Handerson and Pabis, logarithmic, Wang and Singh and Weibull. The models having highest coefficient of determination (R^2) and lowest root mean square error (RMSE) and χ^2 indicates the best model. Sufficient information is not available on drying kinetics of vegetable seeds. Proper knowledge of drying kinetics would help in attaining proper design of dryer for the selected vegetable seeds.

There are different sources of energy for drying. In recent years, focus on renewable energy has tremendously increased as it provides green energy. Among all the renewable resources the most reliable and abundant source is the sun. Therefore, utilization of solar energy become an emerging renewable energy technology that can replenish the shortage of conventional energy sources both in thermal and electrical power output. The annual global radiation in India varies from 1600 to 2200 kWh/m^2 with about 300 clear sunny days in a year providing equivalent energy potential of about 6,000 million GWh of energy per year. Also, government policies encourages use of solar energy for agricultural purpose. Situation is very favourable as The Integrated Energy Policy of India envisages electricity generation installed capacity of 8, 00,000 MW by 2030 and a substantial contribution would be from renewable energy. This indicates that India's future energy requirements are going to be very high and solar energy can be one of the efficient and eco-friendly ways to meet the same (Garud *et. al.,* 2007).

Solar energy can produce both thermal power and electricity. Thermal power is obtained through glass or lenses configuration whereas electricity are obtained through photovoltaic surfaces or solar cells (Sharma, 2011).

Traditional sun drying method takes both large amounts of space as well as long drying time. Uncontrolled weather conditions, contamination of seeds from foreign material or insect infestation are associated with sun drying resulting in slow drying rate and poor quality of the products. The effect of different drying methods such as sun, shade, silica drying and a seed dryer on seed quality were compared by Babiker *et al.* (2010) using sorghum crop. Silica gel and shade drying also give as good alternative methods other than seed dryer. However, sun drying is harmful to the seeds and affects long-term seed viability. However, silica and beads drying methods of seed are associated with another unit operation i.e. separation. Normally desiccant drying is very slow process. Also though some desiccants like silica gel can be regenerated by heating, there is loss of water holding capacity of silica gel due to polymerization after repeated heating. These methods therefore make a non-viable option. On the other hand, mechanized dryers are faster and gives better quality product. However, they require substantial quantities of fuel or electricity to operate, leading to high cost of drying (Tonui *et al.*, 2014). Other than sun and shade drying systems, all require electrical power for operation. The reliability and assurance of grid power, especially in rural India is diminutive. Due to limitations of sun drying and better understanding of utilizing solar energy to advantages give rise to scientific method of solar drying.

As solar energy can provide both thermal and electrical at the same time, it is advantageous to use both in seed dryer. Storage of thermal energy for supply of heat during unavailability or undetermined weather conditions can extent the use of dryer efficiently. It helps in maintaining better quality by reducing thermal stress to the seeds. Also, it was observed that optimum air-flow can be provided in forced convection dryer or hybrid type of dryer. Photovoltaic cell can provide an ideal energy supply for fan used in forced convection dryer.

As sun drying is in vogue in India and other developing countries where solar power is in abundance, it would be prudent to develop low capacity dryer powered with solar energy using its both electrical and thermal capabilities. An urgent need of developing such dryer with automated control of temperature and air flow of the drying air was felt. Evaluation of such a dryer under actual conditions is another important aspect of the study on design and development of the dryer. The test evaluation involves determination of dryer performance parameters as a machine efficiency and also with respect to its intended job i.e. as per the farmer's requirements. Evaluation of seed drying also involves determination of seed quality i.e. germination, vigor, viability, seed health and electrical conductivity in drying process. The germination test aims to provide ideal conditions for germination and to reveal the maximum potential of seed. Top of paper method are most commonly used method for germination test of small vegetable seeds. Seed vigor test provide knowledge about the ability of seed in poor field conditions (ISTA, 2015). Vigor also indicates the rate of germination and seedling growth, both in favorable and unfavorable conditions for germination and emergence in field conditions. The electrical conductivity test measures the leakage of solutes from seeds in the solution, with low-vigor (aged) seeds showing high levels of leakage in comparison with high-vigor seeds. Seed health tests are conducted to detect the infected seeds due to plant pathogen. Poor seed health results in reduction of germination percentage and vigor. This test can be done through visual observation or by using microscope.

Keeping the above considerations in view, the present study was done with the following major objectives:

1) To study drying kinetics and optimization of critical drying parameters for selected vegetable seeds with respect to physiological and seed quality attributes.
2) Design of the automated solar dryer.
3) Techno-economic analysis of the developed solar dryer.

Chapter 2

REVIEW OF LITERATURE

The quality seed in production of vegetables is of paramount importance. Effects of temperature and moisture on seed quality are very pronounced. Unit operations of seed processing that involves are cleaning, grading, drying and storage. Drying is important to remove the moisture to bring to a safe level for storage. Solar energy is an alternative and emerging source used for drying that can replace the conventional energy source. Factors that involves the design, performance evaluation and cost estimation of solar dryer are also discussed. This chapter deals with previous work done related to dryer and research gap in developing solar seed dryer for vegetable seeds.

2. Importance of vegetables seeds

Vegetable are any edible parts of plant which contain valuable food ingredients that can be successfully utilized to build up and repair the body. They are highly beneficial for the maintenance of health and prevention of diseases.

2.1 Vegetable and its health benefits

Vegetables are well known for its nutraceutical properties as they provide essential vitamins, minerals, protein, fiber, phytochemical and other micronutrients. Vegetables can reduce the risk of health problems such as poor vision, gastrointestinal problems, heart disease, stroke, chronic diseases such as diabetes, and some forms of cancer. Phytochemicals rich vegetables provides antioxidants, antiflammatory, enzyme inhibiting and bioactive features which are well known for protection to human against chronic diseases. Overall adequate intake of vegetables could provide nutrition both in qualitatively and quantitatively (Dias, 2012). According to World Health Organization, global intake of vegetables is less than 20-50% of the recommended amount. Consumer’s preferences for convenience foods is also a reason for significantly low vegetable intake in developed countries (Rickman *et al.*, 2007).

Southon (2000) stated that the way of consumption defines the availability of the nutrients to the body e.g. some compound may readily available after cooked whereas some compound may be easily accessible in raw form. Consuming whole foods are more beneficial to human health than isolated components such as those that are found in supplements.

Rais and Sheoran (2015) stated that India is the world's largest producer of many fresh fruits and vegetables. India ranks amongst the world's five largest producers with over 80 % agricultural produce. India produced around 162.187 MTs of vegetables providing 14.0 % of country's share in the world production of vegetables. Most popular vegetables grown in the country are tomato, brinjal, onion, carrot, chilli, cauliflower, cabbage, peas, potatoes, onions and few common cucurbits and leafy vegetables. Out of these popular vegetables, commonly consumed and available throughout the country are onion, carrot and tomato.

Randle (1997) stated that onion is largely consumed for its unique flavour and its ability to improve the flavour of other foods. Also it has high content of polyphenolic flavonoids that have anti-carcinogenic, antithrombotic, antiplatelet, antiasthmatic and antibiotic qualities (Griffiths *et al.,* 2002; Mogren, 2006;Williamson *et al.*, 1996).

Rao *et al.*, (1999) stated Carrots contain carotene, a precursor for vitamin A. It contains the highest amount of beta-carotene (Pearson, 1976). Vitamin A is a potent antioxidant, which are able to shield the cells from oxidative damage and reducing the risks of chronic diseases.

Sanchez-Moreno *et al.*, (2006) mentioned that tomatoes are rich in lycopene which has the property to reduce the incidences of prostate, lung and digestive tract cancers. It also contains high level of folate, vitamin C and vitamin E.

The production of vegetables in India is 1.7x 10^8 tonnes from an area of 9.5x 10^6 hectare in 2014-15. Despite of high production and productivity of vegetable, there is still more to produce to feed the increasing population demand. Also, increase in knowledge on the importance of vegetables on its nutritional benefits both qualitatively and quantitatively, there is increase in demand of vegetables. To yield more production and to fulfil the demand, use of good quality seeds is also one of the deciding inputs.

2.2 Importance of seed

Seed is the basic input for planting or regeneration purpose in agriculture. It is the prime inputs for successful cultivation. Good quality seeds play a pivotal role in crop production and act as the most important catalyst for other inputs to be cost effective. It decides future plant development and consequently successful cultivation. Use of quality seed accounts for 20-25 % productivity. It provides not only higher yield but can also get high monetary returns (Koundinya and Kumar, 2014).

2.2.1 Quality parameters

Lack of information on seed quality could result in crop failures and has potential to threaten food security. To know the seed quality parameters, it is necessary to have broad knowledge about plant and seed physiology, taxonomy and botany with intensive scientific studies and research. Since 1924, the International Seed Testing Association (ISTA) has been the impartial and objective platform where leading seed technologists and researchers have come together to discuss relevant scientific progress and make the necessary definitions regarding seed quality and how to measure it. Some of the main parameters that measure quality of seeds are germination, vigor, viability, seed health and electrical conductivity (Ertsey, 2009).

2.2.2 Germination Tests

A seed is said to have germinated successfully if it has developed to the stage where the appearance of the seedling indicates whether or not it is able to produce a satisfactory plant in favorable field conditions. The result of a germination test is reported as a percentage of normal seedlings, abnormal seedlings, hard (unimbibed), and dead seeds (ISTA, 2015).

The germination test aims to provide ideal conditions for germination and to reveal the maximum potential of seed. The ideal conditions of different species may differ in terms of the substrate, temperature and time. The substrate for germination may be sand, an organic medium, on top of paper or between papers. Temperatures for germination are either constant or alternating, where one temperature is applied for a specified length of time, followed by another temperature for the rest of 24-hour period (ISTA, 2015).

Maryam and Oskouie (2011) studied the effect of mechanical damage at processing on soybean seed germination and vigor. The study revealed that highest amount of electrical conductivity and minimum germination percentage was obtained for maximum mechanical damage seeds. Also, moisture of 12-14 percent had the maximum germination percentage and least mechanical damage whereas 16-18 percent moisture content had the highest mechanical damage and lowest germination ability.

Seed dormancy is also a characteristic to be considered during germination. The presence of dormancy means that the viable seeds will not germinate even when the ideal conditions are present unless they have received a specific environmental cue. Many species require to break the dormancy as a pretreatment requirement for germination test. Physiological dormancy can be broken by dry storage, moist pre-chilling, usually at temperatures of 5-10 ºC for agricultural and vegetable seed and 1-5 ºC for tree seeds; pre-heating; light; and potassium nitrate or gibberellic acid provided during germination. Physical dormancy arises due to a hard seed coat that prevents the uptake of water at the beginning of germination. It can be broken by soaking in water for 24-48 hours, mechanical scarification or acid scarification (ISTA, 2015).

2.2.3 Vigor Tests

Sometimes germination tests may fail to prove the ability of seed to germinate in poor field conditions for example, cold, wet soils. This results in the emergence to study another physiological aspect to seed quality, which has come to be referred as seed vigor (ISTA, 2015).

Low vigor seeds are those which have high germination but poor emergence whereas those giving good emergence are termed as high-vigor seeds. Low-vigor seeds germinate slowly over a long period of time whereas high vigor seeds germinate rapidly to produce a range of seedling sizes. Also, low vigor seeds lose the ability to germinate more rapidly during storage while high vigor seeds have good storage potential. Vigor also indicates the rate of germination and seedling growth, both in favorable and unfavorable conditions for germination and emergence.

The electrical conductivity test measures the leakage of solutes from seeds, with low-vigor (aged) seeds showing high levels of leakage in comparison with high-vigor seeds.

Maryam and Oskouie (2011) stated that mechanical damage of soybean seed may attribute to damage to embryo. The damaged seed embryo and seed coat allows the seed matter to exit causing in higher rate of electrical conductivity. This results in the loss of seed quality including vigor and viability.

The results of a vigor test give a farmer more information about the potential of a seed to perform in a range of soil conditions; a seed company information for managing its seed stocks, both in store and in marketing; a seed producer guidance regarding where seed quality may be reduced and how this can be minimized.

2.2.4 Seed health tests

Seed health tests are conducted to detect whether seeds are contaminated with or infected by plant pathogen. Poor seed health may show disease resulting in reduction of germination percentage and normal seedlings. It also indicates the need for seed treatments.

Seed health testing methods includes testing from direct visual observation to highly sophisticated tests. Direct visual observation may be enough to identify an infected lot if diseased seeds are clearly discolored or have an uneven shape or if there is fruiting bodies.

Another common method of testing includes keeping the seed on moist germination paper or a nutrient medium to allow growth of the pathogen and incubating it for subsequent identification. Growth of fungi can be identified from fruiting bodies and color of their growth (the mycelium) whereas bacteria can be identified from their color, shape and texture of their colonies.

All the mentioned properties are affected by the moisture content. It gives an idea for the seed for long-term and short-term storage and also determine the response of seeds to dormancy breaking techniques and vigor tests.

2.2.5 Moisture content

High moisture content of seed results in mould growth, heating damage, ageing and increased insect image causing decrease in viability. It gives information regarding seed maturity, optimum harvest time, mechanical damage, economics of artificial seed drying, seed longevity and pathogen infestation (Hasanuzzaman, http://hasanuzzaman.weebly.com.).

McCormack (2004) stated that high moisture of seed (greater than 18%) results in loss of vigor and viability during storage and processing. Therefore, it is necessary to reduce the moisture content of seeds to a safe level for storage. Seeds at 18 to 20%, moisture content increased respiration resulting in rapid deterioration of the seed. The rate of ageing and quality deterioration increases with the increase in moisture content.

Harrington (1960) suggested that an increase in seed moisture content of 1% will double the rate at which germination declines. Temperature and moisture content are the two main factors affecting the production of quality seeds**.**

Temperature and moisture content are the important factors affecting seed quality during storage. To increase seed longevity, both temperature (for environment and seeds) and moisture (seeds and air) must be reduced. Maximum quality of seeds are attained at physiological maturity. It is observed from seed physiology that maturation occurs in a non-uniform way resulting in variation in moisture content among the seeds from the same field. Hence, it makes it necessary to perform drying to reduce excess moisture content.

2.2.6 Seed Processing

Seed processing involved various unit operations from harvest till the time of planting such as extraction, cleaning, grading, washing, drying, transportation and storage.

McCormack (2004) stated that **‚s**eeds being living organism and has to maintain its quality from harvest till the time of sowing, it is important to understand how various unit operations in seed processing affects the longevity and vigor of the seed to minimize seed damage during processing. It is desirable to dry the seed fairly quickly because slow drying may result in mould growth or premature sprouting of the seed.

2.3 Importance of seed drying

Drying is one of the most important and sensitive unit operations in seed processing. Drying of seeds involves removing of moisture to a safe moisture level for storage till the time of sowing without or minimum loss in its quality. Seed injury may occur during drying if there is no proper care. Selection of temperature for drying seed is necessary to maintain its quality.

2.3.1 Drying temperature on seed quality

Herter and Burris (1989) studied the effect of drying temperature and drying rate on corn seeds quality. They observed that shelled samples were not injured when dried at 35ºC but lost its viability at 50ºC compare to ear samples. Excised embryos dried at 22-50ºC germinated well even though they dried at rates up to 40%, per hour. Both temperature and drying rate are factors in drying injury.

Hossain *et al.* (2015) stated that seed moisture content can decide whether seed can be stored safely without loss in germination and vigor. An experiment has been conducted to dry maize seeds at 38, 40, 42, 44, 46, and 48 °C in a laboratory dryer. Optimum drying temperature in terms of drying time and seed quality was obtained at 42 ºC.

Siddique and Wright (2003) studied the quality of pea seed at different drying time and temperature. This study confirmed that there is no strict relationship between moisture content and germination percentage of pea seeds. However, it depends on the drying temperature. Drying air of 40ºC for 48h dried the seeds to a lower moisture percentage(8%) but still 96% of seed germinated and found to be the best compared to 60ºC-48h, 80ºC-4h and 100ºC-2h of drying temperature and time. High drying temperature resulted in loss of viability that may be due to internal cracks, split seed coats and discolouration.

Hunje *et al.* (2007) studied the effect of different drying methods on seed quality of two varieties of chilli Byadagi kaddi and Dyavanur local. Better seed quality was recorded from mechanical drying and sun drying of 35 ºC compare to shade drying. Germination percentage, root length, shoot length, seedling dry weight, vigor index and electrical conductivity from mechanical drying were 90.37 %, 8.76 cm, 7.84 cm, 175 mg, 1494 and 1.26 dSm^{-1} respectively. Byadagi kaddi variety recorded better seed quality parameters during drying over Dyavanur local chilli. It was also recommended that temperature not beyond 35 ºC should be used for drying of vegetable seed.

Ennen (2011) examined the effect of maturity stage (green-, yellow-, or brown-pod), drying temperature (27 °C ± 2, 31°C ± 2, or 41°C ± 2), and pod integrity (pod intact or removed) on soybean seed quality. Yellow pod and brown pod seeds dried at ambient temperature (27 ºC) showed similar seed quality. Seed quality get reduced at drying temperature of 41°C ± 2 at both levels of pod integrity for immature harvested seeds (green-pod).

Morrison and Robertson (1978) studied the effects of drying on sunflower seed oil quality and germination. Sunflower seed (SunGro 380) having harvest moisture content 43% w.b. were dried at 35, 53, 72, and 88ºC to a final moisture level of 10% or below with air flow rate of 2000 $m^3/hr/m^3$ seed. There were no effect of temperature on total oil but free fatty acids increased as initial moisture decreased. Germination increased with decreasing initial moisture for a given drying temperature. Also germination increased with decreasing drying temperature at given initial moisture content. It was concluded that drying temperature greater than 53ºC should not be used if seed viability is to be maintained.

Krzyzanowski *et al.* (2006) stated that the maximum range of temperature that can be tolerated by seeds without causing physical and chemical damage is 40.5 to 43.3 ºC. High moisture seeds are more susceptible to thermal damage. It is recommended to use lower temperature for seed having high moisture content and vice-versa. Seed having 10 % w.b. moisture content and below should dry at 43.3ºC, 10-18 % at 42.2 ºC, 18-30 % at 32.2 ºC respectively.

Sveinsson and Bjornsson (1994) studied the effect of seed maturity, drying temperature, and storage temperature on germination and viability in Icelandic Poa pratensis L. The germination rate was increased when the seeds were stored at 20–25 °C compared to 6 °C. Viability of seeds reduced in immature lots when dried at 35 °C and 45 °C compared to drying at 20–25 °C. But there was no effect of temperature when the seed had obtained physiological maturity. Seed dormancy was markedly enhanced with delayed harvest.

Pereira *et al.* (2008) stated that high temperatures resulted in reduction of carrot seed germination. Temperature of 20ºC was found better in germination than 35ºC. However, less aged seed lots had higher germination and vigor at higher temperatures than more aged seeds.

Mobayen (2015) mentioned that smaller seeds had faster rate of germination with lower germination percentage than larger seeds. Temperature and germination rate of tomato seeds could be expressed by parabolic function. The minimum and optimum temperature for germination of tomato seeds was 11°C and 25°C respectively.

Hossain *et al.* (2015) studied the effect of temperature on maize seed germination. Maximum germination percentage obtained was 91.47 % at 42 °C. Germination reduced drastically when the seed dried above 44 °C.

Filho *et al.* (2016) studied the effects of drying temperature and storage on the growth of soybean seedlings. Harvested seeds at 23 % (w.b.) moisture content were dried at different temperatures of 40, 50, 60, 70 and 80ºC upto the final moisture content of 12.5±0.7 % (w.b.) and stored for 180 days. In testing germination and seedling performance for every 45 days, it was observed that increased in drying temperature affects physiological quality. Air temperature of 40 °C can be recommended for drying with storage time of 180 days without climate control.

It was observed from previous researches that temperature and moisture content affects physiological properties of seed during drying and storage. Therefore, it is necessary to study drying kinetics of vegetable seeds to get knowledge about best temperature and safe moisture content for drying and storage.

2.4 Design and development of vegetable seed dryer

Seeds are usually harvested at harvest maturity where the moisture content range from 16-18 % wet basis. It is necessary to dry seed to a safe moisture level of about 8 % w.b. before storing it. Seed quality may loss in slow drying due to ageing whereas fast drying may result in desiccation damage. Therefore, efficient dryer are necessary to bring the seed to safe moisture without losing its quality. Depending upon the species, initial moisture content and resources available, there are different methods for seed drying such as hot air, sun, shade, vacuum, freeze and refrigeration drying (Ellis and Roberts, 1980). To design and select an efficient dryer, it is necessary to study engineering properties of the crop and its drying behaviour.

2.4.1 Role of engineering properties in design of dryer

The knowledge of engineering properties of biological materials including physical, mechanical, aerodynamics, thermal and optical properties is necessary for the design and development of processing equipment. In fact, designing the seed processing equipment without considering engineering properties of biomaterials may yield poor results (Davies and El Okene, 2009).

Altuntas and Yildiz (2007) stated that physical properties such as size and shape, mass, volume, thousand grain weights, porosity, bulk and true densities are necessary for design of various separating, drying, storage, and handling equipments for bulk materials (Tabatabaeefar and Rajabipour, 2005). Thousand seed weight is required to determine theoretical estimation of seed volume (Liny *et al.,* 2013). Designing of drying and aeration system for seeds requires the knowledge of bulk density, true density and porosity of the materials as it affects the resistance of airflow of the stored products (Liny *et al.,* 2013). Low porosity in grain bed provide greater resistance to water vapour or air escape during drying and aeration process, that leads to higher power to drive the aeration fans. The aerodynamic property of the products i.e. terminal velocity is important and required for designing of pneumatic conveying systems, cleaning and separation equipment (Sahay and Singh, 2004).The engineering properties of biological materials are also greatly influenced by the moisture content.

Ilori and Akinyele (2016) investigated the effect of moisture content on engineering properties of Amaranthus Cruentus seed. The properties studied were bulk density, true density, porosity, angle of repose and coefficient of static friction on five structural surfaces (plywood, mild steel, stainless steel, galvanized steel and glass) within the moisture range of 12.48 % db and 20.09 % dry basis. At particular moisture content of 12.48 % db and 17.92 % db bulk density, true density and porosity decreased but increased at 20.09 % db. Angle of repose increased from 21.21° to 33.189° within the moisture range. The coefficient of static friction on all the surfaces decreased from 0.5869 to 0.1406 with increased moisture content. Moisture content has significant effect ($p \leq 0.05$) on engineering properties and the relation can be expressed by the regression models.

Liny *et al.* (2013) studied the physical properties of black gram at 11.11 % moisture content. The average length, width and thickness were found to be 3.53 mm, 2.22 mm and 2.29 mm. True density, bulk density and porosity were 1335.08 kg/m^3,805.091kg/m^3 and 39.69 % respectively. The geometric mean diameter, arthimetic mean diameter, equivalent mean diameter, thousand grain weight, sphericity, aspect ratio, surface area and volume were 2.612 mm, 2.679 mm,4.24 mm,40.6 g, 74.35 %,65.5 %, 21.591 mm^2 and 9.56 mm^3 respectively.

Ilori and Akinyele (2016) examined physical properties of Corchorus olitorius seed as a function of moisture content in the range of 9.86%db and 17.69%db. Bulk density, true density, angle of repose, porosity and coefficient of static friction on five structural surfaces (plywood, mild steel, stainless steel, galvanized steel and glass) were determined using standard methods. Bulk density, true density and porosity decreased from 0.6965 g/cm3 to 0.6146 g/cm3, 1.2223 g/cm3 to 1.1364 g/cm3 and 38.42% to 35.26% respectively within the studied moisture range. Angle of repose increased from 42.79° to 45.34° as the moisture increased whereas the coefficient of static friction on five structural surfaces decreased from 0.7843 to 0.2906 with increase in moisture content for all the contact surfaces. The relationship between the properties and moisture content can be expressed by the regression model.

Mollazade *et al.* (2009) studied physical and mechanical properties of cumin seed within the moisture range of 7.24 % to 21.38 % dry basis. Increasing of moisture content was found to increase the seed length (5.14-5.58 mm), width (1.33-1.55 mm), thickness (0.97-1.05 mm), arithmetic mean diameter (2.48-2.73), geometric mean diameter (1.882.09 mm), thousand seed weight (2.9-3.9 g), porosity (51.22 %-64.11 %), surface area (10.34-12.66 mm^2), true density (917.8-1030.6 kg/m^3), static angle of repose (43-49 deg), dynamic angle of repose (47-56.6 deg), and coefficient of static friction on the three surfaces: glass (0.48-0.77), galvanized iron sheet (0.36-0.73), and plywood (0.57-0.69). However, bulk density was found to decrease from 447.66-369.88 kg/m^3, and rupture force and rupture energy along with seed length and width were found to decrease from 83.74-56.17 N, 132.95-84.47 N, 50.66-27.52 mJ, and 67.8 to 33.36 mJ, respectively. With the increased in moisture content from 7.24% to 14.5% d.b., the sphericity increased from 36.63% to 37.5% and then reduced to 37.5% with further increase in moisture content to 21.38% d.b.

Pandiselvam *et al.* (2014) determined the physical, frictional and aerodynamic properties of onion seed (variety CO 5) as a function of moisture content in the range of 9.8 to 29.6 % (d.b). Size, shape, bulk density, true density, 1000 seed mass, porosity and angle of repose increased with increase in moisture content. Porosity, bulk density and true density, angle of repose and terminal velocity increased from 46.90 to 59.53%, 489.64 to 526.24 and 906.74 to 1283.51 $kg.m^{-3}$, 28.11 to 37.41° and 1.7 to 2.6 $m.s^{-1}$ respectively with the increase in moisture content. Static coefficient of friction on various surfaces (plywood, mild steel, galvanized iron and stainless steel) also increased linearly with increase in moisture content. Plywood surface offered maximum friction whereas stainless steel recorded minimum values.

Aremu *et al.* (2016) determined engineering properties of fluted pumpkin seeds. Average values of surface area, bulk density, true density, sphericity and porosity are 533.38 mm^2, 0.94 kg/m^3, 1.15 kg/m^3, 0.47 and 17.55 %. The coefficient of friction determined on five different structural materials (galvanized steel, mild steel, stainless steel, plywood and glass) obtained least value on glass (0.477) and highest on plywood (0.577).

Ashwini and Vikas (2014) studied the physical and mechanical properties such as bulk density, true density, angle of internal friction, porosity, static coefficient of friction of sunflower seeds as a function of moisture content. The moisture range studied was 10 % to 14 % (w.b).The average length, width, thickness, mass of 100 seeds and angle of repose increased ranged from 12.54 to 12.91 mm, 5.57 to 5.93 mm, 3.88 to 4.36 mm, 6.08 to 6.36 g and 23.9º to 26.8°, respectively as the moisture content increased. But bulk density decreased linearly from 435 to 432 kg/m^3 whereas true density increased linearly from 769.2 to 806.5 kg/m^3. The porosity was decreased from 43.5 to 38.7 % and the static coefficient of friction increased from 20 to 22, 18 to 19, 15 to 16 for wood, galvanized steel and glass surfaces, respectively as the moisture content increased.

Davies (2010) investigated the engineering properties of melon seeds of three different varieties: C. edulis, C. vulgaris and C. lanatus at the moisture content of 6.25, 6.33 and 5.21 % dry basis respectively. The axial dimension, mean diameter, sphericity, surface area, true and bulk density, porosity, angle of repose, coefficient of friction were determined using standard method. Length, width, thickness, arithmetic and geometric diameter, sphericity, surface area and 1000 unit mass ranged from 12.81-14.50 mm, 7.02-8.42 mm, 2.22-2.49 mm, 7.36-8.31 mm, 5.84- 6.54 mm, 0.47- 0.53, 134.64-192.23 mm^2 and 94.0- 110.0 g respectively. The static coefficient of friction was determined at four frictional surfaces, namely, glass, plywood, galvanized steel and concrete, where the highest was observed in concrete surface for all three varieties of melon seeds.

Bamgboye and Adebayo (2012) studied the moisture-dependent physical and mechanical properties of Jatropha curcas within the moisture range of 5.85 to 25.85 % dry basis. All the properties investigated including length, width, thickness, thousand grains mass increased as the moisture content increased. The coefficient of friction increased linearly against various surfaces with increased in moisture content.

The bulk density and true density, porosity increased from 428 to 474 kg/m^3 and 863 to 1035 kg/m^3 and 50.3 to 54.2 % respectively, with increase in moisture content. The maximum and minimum rupture force was 113.99 N and 26.83 N respectively in horizontal loading position and transverse loading position. The maximum and minimum deformation obtained was 2.5 mm and 0.40mm in horizontal and vertical position.

2.4.1 Drying Kinetics

Fernando and Amarasinghe (2016) mentioned that mathematical modelling and simulation of the drying curve can be used to study drying variables and to optimize drying parameters and conditions. Modelling of drying curve can satisfactorily describe the drying behaviour.

Khazaei and Daneshmandi (2007) studied the mathematical and neural networks modeling of drying kinetics of sesame seeds. Forced convection and natural convection were employed under indoor conditions. Constant air velocity of 1m/s and air temperature and relative humidity in the range of 25-29 °C and 35-40 %, respectively were used for forced convection drying. For natural convection, air temperature and relative humidity were in the range of 32-36 ºC and 30-35 % respectively. Drying data were fitted to thin-layer drying models, namely, Khazaei, Peleg, Page, Handerson and Pabis, logarithmic, and Weibull. Artificial neural network was used to find the correlation between moisture ratios with drying time and drying method.

Hasan (2010) studied the effects of drying air temperature of hybrid rice seed. Drying performance and quality in terms of germination capacity and colour were studied. In drying the seeds from 22 % (wb) to equilibrium moisture content at 40 ºC, 50 ºC and 60 ºC, the time required were 540 minutes, 250 minutes and 200 minutes respectively. Drying temperature had significant effects on the seed germination capacity giving maximum percentage at 40ºC drying air temperatures. Thin layer drying models such as Midilli *et al.,* two term exponential, Page, Henderson and Pabis and Newton model were used to fit the data. The models having highest R^2 and lowest RMSE indicates the best model. There were no effects of drying temperatures on colour of paddy.

Roberts *et al.* (2008) studied the drying kinetics of grape seeds. Seeds were dried at 40, 50, 60 ºC and constant air velocity of 1.5 m/s. Equilibrium moisture content had a significant effect on the normalized drying curve and was determined at each drying temperature. Among the thin layer drying models viz. Page model, Lewis model, and Henderson–Pabis model, Lewis model was found the most fitted model (per cent error less than 5 per cent).

Cantu-Lozano *et al.* (2013) investigated the drying kinetics of grapefruit seeds at different temperature of 40, 50, 60 and 70°C and at three air velocities of 0.6, 1.0 and 1.4 m s^{-1}. Drying of grapefruit seeds took place under the falling rate period. Three thin-layer models viz. Page, Lewis, and Henderson-Pabis model were used to predict the drying curves. For all drying air temperatures and velocities, the Page model presented the best fit.

Motri *et al.* (2013) investigated the drying kinetics of prickly pear seeds. Drying was performed at air temperature of 45 and 70°C and at relative humidity of 15 and 35 % and air velocity of 1 and 2 m/s. Only falling rate period was detected from the drying curve. Drying rate increased with the increased in temperature and air velocity. Out of seven models studied, according to statistical parameters (correlation coefficients and standard errors), Verna model was found satisfactory in describing the drying curve.

An experiment was conducted by Bchir *et al.* (2012) to study effect of air-drying conditions on physico-chemical properties of osmotically pre-treated pomegranate seeds. The drying air temperatures were 40 °C, 50 °C and 60 °C with air velocity of 2 m/s. The properties studied were antioxidant capacity, total phenolics, colour and texture. It was observed that osmotic dehydration and air-drying temperature have a significant influence on the quality of seeds. Air drying temperature of 40ºC was recommended for drying as it gives lowest impact to the quality of seeds.

Sogi *et al.* (2003) observed that Henderson model can describe sorption isotherm of tomato seeds over the entire studied temperature range (30, 40, 50, 60, 70ºC) by static method. On drying the tomato seeds in cabinet/fluidised bed dryers at 50, 70 and 90 ºC using tray load of 4, 8 and 12 kg/m^2, it was observed that drying rate took place under falling rate period. Page's model can adequately describe the drying behavior.

Sacilik *et al.* (2003) conducted an experiment to determine the drying characteristics of hull-less seed pumpkin under different drying methods viz. hot air, solar tunnel and open sun drying. The studied temperature range for laboratory hot air drying was 40-60 ºC at constant air velocity of 0.8 m/s. A low cost solar dryer was constructed using locally available materials for solar drying experiments. Fick's law described the moisture transfer from the sample. The data were fitted to various thin layer drying models viz. Page, Henderson and Pabis, logarithmic and two-term models. Non-linear regression analysis was employed to find the drying rate constants and coefficients of models. The best model was selected based on the best statistical indication.

Mirzaee *et al.* (2009) investigated the mathematical model for thin layer drying of *Viliamz* cultivar of soybean. Drying experiments were conducted at different inlet drying air temperatures of 30, 40, 50, 60 and 70ºC and at a fixed air velocity of 1m s^{-1}. Non-linear regression analysis was conducted to compare different thin layer mathematical drying models according to R^2 values, RMSE, $\chi 2$ and error fraction. Multiple regression analysis was employed to study the effect of drying air temperature on the model constants and coefficients. The best mathematical equation for modelling thin layer drying of soybean was found to be Midilli *et al.* model.

2.4.2 Energy source in drying

Energy plays a significant role in generation of wealth and economic development. Limited available of fossil resources and its associated problems to the environment make aware to focus on sustainable energy supplies that use renewable energies. Renewable energies include the energy source from sun, wind, water, tidal, wave, geothermal and biomass. All the sources of renewable energy are geographical dependent except sun. For example, wind and water source are mostly available in coastal and mountain regions. Solar energy can also produce both thermal and electrical power. Therefore solar energy becomes an emerging renewable energy technology that can replace the shortage of conventional energy sources both in thermal and electrical power output. Also, utilization of energy and its management in agricultural become an important research area to provide sustainable production to fulfil the demand of the increasing population.

India is endowed with rich solar energy resource. The annual global radiation in India varies from 1600 to 2200 kWh/m^2 with about 300 clear sunny days in a year providing equivalent energy potential of about 6,000 million GWh of energy per year. The daily average solar energy incident over India varies from 4 to 7 kWh/m^2 with about 1500–2000 sunshine hours per year (depending upon location). The Integrated Energy Policy of India envisages electricity generation installed capacity of 800 000 MW by 2030 and a substantial contribution would be from renewable energy. This indicates that India's future energy requirements are going to be very high and solar energy can be one of the efficient and eco-friendly ways to meet the same (Garud and Purohit, 2007).

Sharma (2011) mentioned that solar energy can produced both solar thermal power and electricity through concentrating photovoltaic. Solar thermal power can be generated by converting the sun's energy into high temperature heat through a medium such as glass or lenses configuration. This are mostly used for heating water and cooking purposes. Concentrating photovoltaic system is a method of generating electricity directly from the sun's rays through photovoltaic surfaces or solar cells.

2.4.3 Limitation of commonly used seed dryer

Al-Jumaah *et al.* (2014) mentioned that most common traditional method of drying agricultural produce is sun drying. However it is associated with various drawbacks. It takes both large amount of space and long drying time. The products may damage due to uncontrolled weather conditions, contamination of crops from foreign materials or insect infestation resulting slow drying rate and poor quality of the products. Because of the limitations of sun drying and better understanding of utilizing solar energy to advantages give rise to scientific method of solar drying.

Mechanized dryers are faster and give better quality product. However, they require substantial quantities of fuel or electricity to operate, leading to high cost of drying (Tonui, 2014).

Babiker *et al.* (2010) investigated the effect of low cost drying methods on the seed quality of different genotypes of sorghum. Five genotypes were subjected to different drying methods namely sun, shade and silica gel. All the drying methods were compared to the standard recommended drying condition using a seed dryer (Munter seed dryer Model M120). The quality parameters studied were moisture content, germination percentage, viability and quality were studied. All the drying methods can bring the seeds to a safe moisture level (range of 5.6 - 7.5 %) but seed dryer performed the best as far the quality is concerned. Silica gel and shade drying also give as good alternative methods. However, sun drying is harmful to the seeds and affects long-term seed viability.

Hay *et al.* (2012) stated that desiccant drying using drying beads can bring down the moisture content of paddy seed at a very low level at low temperature and humidity. The seed and the beads are mixed at different proportions with slide variation of temperature.

However, bead drying or silica drying can be used for only with desiccation-tolerant(or“orthodox”)seeds(Anonymous,horticulture.ucdavis.edu/main/overview_beads.pdf). As the seeds are mixed with beads, it is necessary for separation again at the time of sowing resulting in involvement of another unit operation that may cause mechanical injury to seed as well as cost increment.

Also, refrigeration and vacuum drying methods are high cost, high power consumption and require technical person to operate. Therefore, it is necessary to choose an alternative and efficient dryer system that are cost effective and less or no damage to seed quality during drying operation.

Gavhale *et al.* (2015) developed small scale village level solar seed dryer. It works on the principle that, increase in temperature results in rise of absolute humidity but decrease in relative humidity providing more capacity of the air to take up the moisture from its surrounding. Drying time of the product can be reduced either by heating the air or reducing the relative humidity of the surrounding. It consists of tray, reflective walls and glass roof, a preheating air absorber plate, inner panels for removal of moisture and chimney through which air stream passes across the dryer. The dryer could attain 47 ^{o}C inside the chamber. Drying rate obtained from the developed dryer was found higher and showed less risk of spoilage compare to open sun drying.

Ghosal (2012) fabricated a photovoltaic integrated solar dryer and tested for drying of fruits and vegetables. A direct current fan powered by photovoltaic cell has been incorporated in the system to create forced air circulation in transferring thermal energy for drying without the use of grid connected power supplies. The dryer has been coupled to a solar air heater having a sun-tracking facility and blackened absorber for enhancing solar energy absorption. The system consisted of a photovoltaic panel, solar air heater and a drying chamber with chimney. This system can be used for drying various agricultural products like fruits and vegetables. In this work, the experimental study was conducted for the forced mode of drying under no load conditions.

Bennamoun (2013) studied the integration of photovoltaic (PV) cells in solar drying system. Using PV cell in association with solar collector not only improves the efficiency up to 70 % but also provides the electrical energy which is required by other drying system components such as fans providing instantly or stored in battery. The main application of PV cells is their use in direct- and indirect-type forced convection dryers, generally for food and herb drying. In a study case, an economic analysis has shown that payback is dependent on the ratio of the PV cell surface to the total solar collector surface, with the possibility of an optimum payback in less than one year. In another study case, an additional heat pump significantly improved the performance of the photovoltaic–thermal (PV/T) solar dryer, reaching an efficiency of 70 %. A proper design of solar drying is influenced by different parameters such as surface of the PV cell, geographical location, and materials used.

Hegde *et al.* (2015) stated that solar dryers are specialized devices that can control the drying process and protect agricultural products. Solar drying can generate higher temperature, low relative humidity resulting in lower product moisture content and less spoilage compare to sun drying. Drying time of solar dryer reduced by 20 % compare to open drying and produced better quality products. Solar dryer can be classified as namely forced air circulation or active solar dryers and natural air circulation or passive solar dryers according to mode of heating. Forced convection dryers are more efficient and can dry the product faster with superior quality product than natural convection dryers. A low cost, indirect, active-type, environmentally friendly, solar dryer has been designed and fabricated to dry banana. The dryer consists of drying chamber, solar flat plate air heater with three layer of insulation and a fan with a regulator to induce required air flow in the system. For the same solar energy input, bottom flow provided 2.5 °C higher temperature than the top flow. The efficiency of the bottom flow configuration was found to be 38.21% whereas that of top flow configuration was 27.5 per cent.

Tonui *et al*. (2014) designed and fabricated a solar grain dryer using locally available materials incorporated with a biomass burner to overcome the limitation of open sun drying. The components of the dryer consist of solar collector, drying chamber, back-up heater and airflow system. To reduce moisture content from 21% to 13 % w.b. of 100 kg maize in 6 h, a minimum of 3.77 m^2 solar collector area is required in the study area (Nakuru Country, Kenya). The designed dryer has collector area of 0.6 m^2 and employed forced convection to reduce drying time. The thermal efficiency of the developed solar dryer was 57.7 % where 17.8 % has been improved due to the back-up heating system.

Ogheneruona and Yusuf (2011) designed and fabricated a natural convection solar dryer to dry tapioca. The dryer has a minimum of 7.56 m^2 solar collector area to dry a batch of 100 kg *tapioca* in 20 hours to reduce the moisture content from 79 % and 10 % wet basis, respectively. The average ambient conditions of the study area (Warri (lat. 5°30', long. 5°41')) Nigeria are 32 ºC air temperatures and 74 % relative humidity with daily global solar radiation incident on horizontal surface of 13 MJ/m^2/day. The optimal drying temperature of cassava products was found to be 52 ºC and final moisture content of *tapioca* for storage is 10 % wet basis.

Stephen and Emmanuel (2009) improved an existing cabinet grain dryer to optimize efficiency at low cost, reduce total drying time and to produce viable and quality grain. Heated air of about 35-40 °C was blown across the grains by a fan through an electrical heating coil. There is an automatic control of the dryer using a thermostat which turns off the machine if inlet temperature exceeds 40 °C. Drying of grains was faster and safer compare to the previous design where gas was used as energy source. It supplied heat through heater and a fan to distribute the heat evenly to the grains in drying chamber.

Raju *et al.* (2013) designed and constructed a solar dryer to dry vegetables after preliminary investigations of drying under controlled conditions (laboratory dryer). 20 kg of fresh vegetables having moisture content from 89.6 % to 13 % wet basis is expected to reduce from collector area of $1m^2$ in two days under ambient conditions. The developed prototype has 1.03 m^2 solar collector area employed with water heating system to recover the waste heat getting from the dryer. Hence the practical usage of dryer is greatly increased by employing the water heating system along with dryer.

Dasin *et al.* (2015) evaluated the performance of a multipurpose passive solar food dryer which was enhanced with a heat storage device. The dryer was used to dry yam, tomatoes, pepper and fish. The performance evaluation results showed that it took 3 hours, 2.5 hours, 10 hours to dry yam, tomato and pepper and fish in solar dryer compare to 8 hours, 6hours, 24 hours by open sun drying. The dryer efficiency for yam, tomatoes & pepper and fish are 33.0 %, 19.3 % and 6.6 % respectively. The thermal efficiency of the developed solar collector is 60 %. It can be concluded that solar dryer is more efficient and consume less time compare to open air sun drying.

Balogun *et al.* (2014) investigated the dryer performance of the developed and fabricated dryer for pumpkin seeds. The dryer material was selected based on availability, cost, maintenance friendly and energy requirement. It consisted of dying chamber, tray, and temperature controller, and heat sensor, fan controller, heating elements, vent and fan. The system drying efficiency was found to be 53.2 per cent.

Folaranmi (2008) designed and tested a passive solar maize dryer. The working principle of the dryer is based on the supply of preheated warmed air through a low pressure thermosphonic solar energy air heater or collector. It consists of collector made up of insulating material (polystyrene) (100 mm x 50 mm x 25.4 mm), absorber plate made up of (aluminium) sheet painted black (100 mm x 50 mm) and a cover glass (5 mm thickness, 100 mm x 50 mm) to contribute overall heating to the dryer. A temperature of above 45 ºC was obtained inside the drying chamber. The moisture content can be reduced to about 12.5 % in three days of 9 hours each day of drying from 50 kg of maize. The products are located on trays inside an opaque drying chamber making the solar radiation does not directly fall into the crop. Thus, it works as a passive solar dryer. The heated air from the collector is ducted to the drying chamber.

2.5 Performance evaluation

Vidyasagar *et al.* (2013) designed solar dryer for vegetables. The dryer works on the principle of greenhouse effect and thermosiphon principle. There is an air vent (inlet) where air enters and guide the air to solar collector and then heated up by greenhouse effect. The hot air then pass through the trays where foods are kept and dried the product. The moisture is removed through the air vent (outlet) near the top of the shadowed side. The food is dried under free convection and it is passive solar system. To collect the waste heat from the exhaust door, a heat exchanger consists of copper tubes for heating water is provided.

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Vlachos *et al.* (2002) designed, constructed and evaluated a solar assisted small-scale tray dryer. The dryer is equipped with a solar air heater, a solar chimney and a heat storage cabinet. The performance of the dryer is tested under adverse weather conditions (i.e. cloudy and rainy) and during night operation. Seasonal weather variations has effect on solar assisted crop dryer where wet season drying gives poorer drying compare to dry season conditions. The operation of a solar-assisted dryer can be extended in night hours through the thermal storage during the day, preventing the rehydration of the products from the surrounding (Aboul-Enein *et al.*, 2000). The drying chamber has (1.3 x 1 x 0.7) m outer dimensions with insulation at the inside walls. The walls are constructed with black painted aluminum sheet of 1.5 mm thickness. A 2.5 cm thick fiberglass layer is used for insulation. Moisture content, velocity, temperature, relative humidity inside the dryer was measured through a microprocessor. Total solar radiation, ambient temperature, relative humidity, wind speed and wind direction were recorded at the meteorological station for every 1 h intervals.

Ogheneruona and Yusuf (2011) designed and fabricated a direct natural convection solar dryer to dry tapioca based on preliminary investigations. The dryer was designed based on amount of moisture to be removed, daily sunshine hours for the selection of the total drying time, quantity of air needed for drying, daily solar radiation to determine energy received by dryer per day and wind speed. 100kg tapioca having moisture content of 79% can be dried upto 10% w.b. in 20 hours with a minimum solar collector area of 7.56 meter square with sample thickness of 3mm. The weather conditions studied are of Wari, Nigeria. A designed and fabricated dryer has a minimum collector area of 1.08 meter square.

Sansaniwal and Kumar (2015) fabricated a natural convection indirect solar dryer for ginger drying. The system consisted of a drying chamber (0.41 m × 0.45 m × 0.53 m) which was properly insulated to minimize heat loss and solar collector (1.3 m × 1 m) which had black coated galvanized iron sheet with thermocole insulation for air heating. The system was assisted with hygrometer (model HT-315) and thermocouple (PT-100 with accuracy ± 0.1˚C) to monitor relative humidity and temperature both at drying chamber and solar collector.

Tonui *et al.* (2014) designed and fabricated solar dryer for maize grain. The design was made according to the moisture to be removed, harvesting period and other environmental parameters such as sunshine hours, solar radiation and wind speed. The size of the dryer was determined according to the drying area needed per kilogram of maize grain. The drying temperature was decided based on the maximum limit of temperature the grain might support. The maximum allowable drying temperature of maize grain is 50 °C without compromising its quality with final moisture content for safe storage as 13 % wet basis.

Rathnayake *et al.* (2006) design and fabricated an engineering model of a crop dryer. The aim is to develop a compact drying cabinet for small scale processing of agricultural products. The designed dryer has the capacity of 50-100 kg of fresh produce with thin layer drying. The cabinet dryer has three main components, namely, drying chamber, air distribution unit and hot air supply unit. The fabricated dryer was evaluated that include assessing of performance in air and temperature distributions, developing of drying curves and analyzing the quality of final products.

Aiswarya and Divya (2015) stated that in an indirect solar dryer thermal energy storage system can be used. The energy storage system can be of sensible heat storage and latent heat storage. Sensible heat stored the internal energy by raising the temperature of the materials which may be solid or liquid. The change in temperature is then utilized during the process of discharging and charging. However, latent heat storage undergoes phase change of the energy store materials. Thus, using the thermal storage system, the dryer can be operated even during unfavorable weather conditions.

Hegde *et al*. (2015) designed, constructed and evaluated a solar dryer for banana. The dryer was constructed using locally available material such as plywood, stainless steel, mesh, wooden skewers, clear glass, galvanized iron sheet and axial fan for operation of the dryer. An indirect type solar dryer was employed to prevent colour and nutrient loss. Flate plate collector made of galvanized iron sheet of 0.6 mm thick was used as it is good conductor, easy to fabricate and economical. The thickness of the collector is 5mm and it was painted black. Plywood was selected as insulating material. A layer of air gap between two plywood sheets is provided to reduce heat loss. Aluminium foil is wrapped on the inside of the chamber to avoid moisture absorption by wood and to reduce heat loss. An axial flow fan was selected to ensure constant flow rate of air based on the calculations of pressure drop in the system. The thickness of banana slices was selected to be 4–5 mm and air flow rate of 3 m/s.

2.6 Cost estimation

Stephen and Emmanuel (2009) conducted cost analysis of the improved existed cabinet grain dryer. Cost analysis of the dryer was done taking each component into consideration. The total cost is divided into material, production and miscellaneous costs. Material costs include frame and casting; production cost includes labor cost, cost of machining components, cost of electrodes for welding and other consumables e.g. cutting and filling stones and miscellaneous cost include transportation, report writing and research cost.

Anonymous (1993) reported that The Institute of Agricultural Engineering and University Of Philippines Los Banos developed a cabinet type hybrid solar biomass dryer (Model FD-50) having capacity of 50 kg/batch. The dryer was designed based on the preliminary experiments conducted under controlled conditions to determine the optimum drying parameters such as drying air temperature and the flow rate and thickness of fruit slices to achieve best quality product. The performance test showed that a batch of 50kg of sliced pineapple with an initial moisture content of 85 % (wet basis) could be dried to a final moisture content of 20 % in about 18 hours at a drying temperature of 60 ^{o}C. A recovery rate of 10 kg of pineapple fruit was obtained. Cost-benefit was computed based on i) number of batches per year ii) cost of pineapple ii) cost of fuel iv) dryer operator cost per batch v) cost of labour per hour per person vi) cost of dried pineapple vii) electricity cost viii) depreciation (straight line method) ix) repair and maintenance x) interest rate.

Mumba (1995) developed and field tested a solar maize dryer in cooperating with a directly coupled photovoltaic (PV) powered DC fan in Malawi, Central Africa having capacity of 90 kg. The incorporation of a PV driven fan provided some form of passive control over the air-flow and hence the drying air temperature. It is coupled with solar air heater having collection efficiency of 80 %. Compare to sun drying it can reduce the drying time by 70 %. Although the capital cost of the dryer was high, the dryer was found to be cost effective with a payback period of less than one year.

Chapter 3

MATERIALS AND METHODS

Design of vegetable solar seed dryer requires knowledge about seeds properties, dryer parameters, drying kinetics information about solar power harvesting mechanism and their relationship. Proper drying process is a pre requisite for safe storage of different seeds more in case of vegetable seeds. The quality of the seed has to be maintained from the time of harvest till sowing. Therefore, the dryer should be designed in such a way that, proper drying kinetics and mechanism is achieved and of the design factors or parameters should not affect the quality of the seeds. Also, to design an efficient solar dryer of vegetable seeds, it is required to study the engineering properties and quality parameters of the seed, drying kinetics, functional design and fabrication and assembly procedures; in addition performance evaluation methods of the developed dryer are equally important to achieve an efficient design. To ensure the quality of the seeds, proper control of temperature through electronic circuit for automated functioning was also required.

This chapter includes the materials used and methodology applied in experiments conducted for development of solar operated vegetable seed dryer with temperature automation. The number of dependent parameters with their levels and response variables for all the experiments are also presented. The selection of the materials, methods and procedure used for obtaining design values, development of the dryer and its performance evaluation were studied.

3.1 Determination of engineering properties of vegetable seeds

Three vegetable seeds, namely, onion, carrot and tomato were selected to study engineering properties for development of the dryer. It was necessary to study the engineering properties of the selected vegetable seeds to determine the ranges of design values of components of the dryer. The engineering properties required to study the design of dryer included bulk density, true density, porosity, arithmetic mean diameter, geometric mean diameter, sphericity, surface area, test weight, coefficient of friction and angle of repose. The engineering properties of the biomaterials changes with moisture content. Therefore, it was necessary to study the variation in engineering properties of vegetable seeds with moisture content. Four levels of moisture content were selected for the study of the engineering properties of seeds, Table 3.1.

Table 3.1 Plan of experiment for determination of engineering properties

<table>
<tr><th>Sl. No.</th><th>Variables</th><th>Levels</th><th>Response variables</th></tr>
<tr><td>1.</td><td>Moisture content</td><td>8,12,16,20 %w.b.</td><td rowspan="2">• Bulk density
• True density
• Porosity
• Arithmetic mean diameter
• Geometric mean diameter
• Sphericity
Surface area
• Test weight
• Coefficient of friction
• Angle of repose</td></tr>
<tr><td>2.</td><td>Type of seeds</td><td>Onion, carrot and tomato</td></tr>
<tr><td></td><td colspan="3">Replications=3
Type of seeds=3
Total no. Experimental run=4x3x3=36</td></tr>
</table>

3.1.1 Sample preparation

The vegetable seeds of tomato, carrot and onion were collected. The seeds were cleaned manually to remove all foreign materials including immature and broken seeds. The initial moisture content was determined by oven drying method (ISTA, 2015). The seed samples of 4.5±1g each were dried at 130±2 ºC for 1h ± 3 min for carrot and tomato whereas onion was dried at 103±2 ºC for 17 ±1 h. Desired moisture contents of the samples were obtained by adding the amount of distilled water as calculated from the following relation (Sacilik *et al.,* 2003):

$$Q = \frac{W_i (M_f - M_i)}{(100 - M_f)} \qquad ...(3.1)$$

Where,

W_i = Initial mass of sample in kg;

M_i = Initial moisture content of sample in % d.b.;

M_f = Final moisture content of sample in % d.b.

The moistened samples were kept in tightly sealed High Density Polyethylene (HDPE) bags. The moisture was allowed to distribute uniformly throughout the sample by keeping it in refrigerator at 5^0C. Before the start of experiment, samples were taken out and kept at room temperature for about 2 hours to equilibrate. The engineering properties were determined at four moisture levels within the range of 20±1% to 8±1% wet basis. The upper and lower limits of moisture content were selected based on the moisture content during harvesting and for safe storage. The different engineering properties were determined in the following manner (Plate 3.1).

3.1.2 Bulk density

The bulk density is defined as the ratio of mass of bulk of grain to the volume occupied by it including the air space. It was necessary to determined bulk density in heat load calculation as well as it affects the resistance of air-flow during drying. It was determined by filling a box of known volume with known mass of seeds. A box of standard size 5cm ×5cm ×5cm was filled with seeds up to the top level. The top level was striked off and the selected sample was weighed (Mohsenin, 1970). The excess seeds were removed to bring the top surface perfectly level. The amount of seeds in the box was weighed using an electronic balance (least count, 0.001g), Plate 3.1 (a). The bulk density was calculated using the following formula. A total of 10 replications were done for each seed selection:

$$\textit{Bulk}\ \text{density}, \rho_b\ (\text{kg/m}^3) = \frac{\text{weight of seeds (kg)}}{\text{Volume of seeds (m}^3)} \qquad \ldots(3.2)$$

3.1.3 True density

The true density (kg/m^3) is defined as the ratio of mass of seeds to the true volume of seeds (Deshpande *et al.,* 1993). It was determined using liquid displacement method (Shepherd and Bhardwaj, 1986). Toluene was used to prevent the absorption during measurement as it has low surface tension compare to water (Sitkei, 1987; Ogut, 1998), Plate 3.1(b). The volume of displaced toluene (C_7H_8) was recorded by immersing a 5 gram of seeds in 50 ml of toluene in a graduated measuring cylinder (Tavakoli *et al.,* 2009). The ratio of weight of seeds to the volume of displaced toluene gave the true density. Seed density was evaluated using the methods suggested by Williams *et al.,* 1983.

$$\text{True Density}, \rho_t\,(\text{kg/m}^3) = \frac{M_s}{V_s} \qquad \ldots(3.3)$$

Where,

M_s = mass of solid particle

V_s = volume of toluene displaced

3.1.4 Porosity

Porosity (ε) is defined as the percentage of void space in the bulk grain that are not occupied by the grain. Bulk with low porosity are more resistant to fluid flow and thus are more difficult to dry, heat, or cool whereas high porosity provides a better passage for air to flow resulting in fast drying and less power requirement of fans and pump. It was determined by the following formula.

$$\varepsilon = \frac{(\rho_t - \rho_b)}{\rho_t} \times 100 \qquad \ldots(3.4)$$

3.1.5. Determination of geometric properties i. e. Arithmetic mean diameter, Geometric mean diameter, Sphericity and Surface area

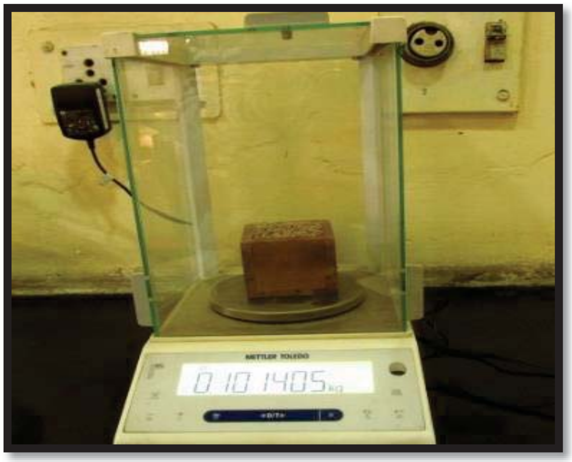
Study of geometric properties provides the idea of size and shape of the seeds. It was necessary to study for cleaning the seeds from the foreign materials as well as to evaluate the size of perforation of trays for the dryer. The geometric properties were determined using the following methods.

Hundred seeds each of onion, carrot and tomato were randomly selected to measure the axial dimensions. A digital Vernier caliper (Mitutoyo Corporation, Japan, ± 0.01 mm) was used to measure the dimensions viz. minor diameter thickness (T), intermediate diameter width (W) and major diameter Length (L), Plate 3.1 (c). The arithmetic mean diameter (D_a) and geometric mean diameter (D_g) in mm were determined from the average of axial dimensions using the formula (Mohsenin, 1970, Joshi *et al.,* 1993).

$$D_a = \frac{L + W + T}{3} \qquad \ldots.(3.5)$$

$$D_g = (LWT)^{1/3} \qquad \ldots..(3.6)$$

The ratio of the diameter of a sphere of the same volume as the object to the diameter of the smallest circumscribing sphere is defined as sphericity (ϕ). It is also



(a) Weighing sample using Electronic Weighing Balance for bulk density.

(b) True density measurement using volume displacement method.

(c) Measurment of seed dimensions using Digital vernier calliper.

(d) Determination of coefficient of friction using coefficient of friction apparatus.

(e) Angle of repose measurement using angle of repose apparatus.

(f) Terminal velocity measurment apparatus.

Plate 3.1. Different apparatus used for measurement of engineering properties of the seeds.

calculated as the ratio of geometric mean diameter of the object to the major diameter (Mohsenin, 1980).

$$\phi = \frac{(LWT)^{1/3}}{L} \qquad \text{….(3.7)}$$

Surface area "A" was determined in accordance with methods reported by Mohsenin, 1986; Orji, 2001; Olukunle and Atere, 2001; Asoiro and Anthony, 2011; Ajav and Ogunlade, 2014 as:

$$A = \pi D_g^{\ 2} \qquad \text{….(3.8)}$$

Where: D_g is the geometric mean of the length, width, and thickness

3.1.6 Test weight

Test weight of vegetable seed provides an idea about the mass of the seeds and thus the load that can be accommodated the tray. The test weight of each sample was determined by counting one thousand seed from each samples and measured in an electronic balance to an accuracy of 0.01g. A total of ten replication were done for each seed.

3.1.7 Coefficient of friction

Coefficient of friction gives an idea about the interaction of the seed and the tray materials, thus helping in the selection of tray materials. The static coefficient of friction for different seeds at different moisture levels was determined on four structural surfaces (wood, mild steel, aluminium and galvanized iron) using inclined plane method which included of a hollow cylinder (50 mm diameter and 50 mm depth) open at both ends and filled with seeds, Plate 3.1 (d). With the cylinder resting on the surface, the surface was tilted gradually by an incorporated screw jack until the filled cylinder just started to slide down. The angle of inclination was observed read from the graduated protector attached to the apparatus (Razavi and Milani, 2006; Varnamkhasti *et al.,* 2008). The coefficient of friction was calculated from the following relationship.

$$\mu = \tan\alpha \qquad \text{….(3.9)}$$

Where, 'μ' is the coefficient of friction and 'α' is the angle of tilt in degrees.

A total of ten replications of each three selected vegetable seed were done.

3.1.8 Angle of repose

The angle of repose is the angle with the horizontal at which the material will stand when piled. The angle of repose of seeds at different moisture contents was measured by emptying method using bottomless cylinder (300mm diameter and 500mm height). The cylinder was placed at the center of a raised circular plate and was filled with the seeds, Plate 3.1(e). The cylinder was raised slowly until it formed a cone on the circular plate. (Taser *et al.,* 2005; Kaleemullah and Gunasekar, 2002).

3.1.9 Terminal velocity

Determination of terminal velocity was necessary to evaluate the maximum air velocity that can pass through the grain during drying. Terminal velocities of different seeds at different moisture content was measured using a cylindrical air column (Joshi *et al.,* 1993; Baryeh and Mangope, 2002), which consisted of a vertical acrylic tube attached to a centrifugal blower. Wire meshes were placed at the bottom of the tube to get uniform air velocity throughout the entire cross section area. 5g of seed was dropped into the air stream from the top of the air column, in which air was blown to suspend the seed in the air stream, Plate 3.1 (f). The air velocity was measured using a hot wire anemometer having a least count of 0.01 $m.s^{-1}$ when the seeds get suspended in air column. A total of ten replications of each three selected vegetable seed were done.

3.2 Experiment on drying kinetics of vegetable seeds

Experiments were conducted to determine the drying kinetics of the selected vegetable seeds. Drying was carried out at three different levels of moisture content. The levels of temperature for drying seeds were decided from literature keeping in mind about the quality deterioration of vegetable seeds at high temperature. The response parameters studied were equilibrium moisture content (% d.b.), rate of drying and moisture ratio. The upper and lower limits of moisture content were selected based on the moisture content during harvesting and that for safe storage. A balanced full factorial (3x3), CRD with three replications was employed for determination of experimental runs and analyzing the corresponding responses, Table 3.2.

Table 3.2 Plan of experiment on drying kinetics of vegetable seeds

<table>
<tr><th>Sl. No.</th><th>variables</th><th>Levels</th><th>Response parameter</th></tr>
<tr><td>1.</td><td>Temperature</td><td>30, 35, 40 ºC</td><td rowspan="3">• Equilibrium moisture content (% d.b.)
• Rate of drying
• Moisture ratio</td></tr>
<tr><td>2.</td><td>Type of seeds</td><td>Onion, carrot and tomato</td></tr>
<tr><td></td><td colspan="2">Replication =3
Type of seeds=3
Total no. experimental run = 3x3x3=27</td></tr>
</table>

3.2.1 Experimental procedure for drying

Moistened samples of all the vegetable seeds weighing 5±0.1g each were dried at constant temperature of 30, 35, 40ºC in convective hot air oven dryer with control temperature. The samples were dried up to a safe moisture level of 8±1 % w.b. of all the three vegetable seeds at different levels of temperature. The reduction in moisture was recorded for every 15 minutes until it came to almost constant value. All the experiments were replicated three times.

3.2.2 Dry basis moisture content

The moisture content (wet basis) obtained with time during drying process was converted into dry basis moisture content for subsequent calculation in drying kinetics.

$$MC\,(\%\,d.b.) = \frac{W_w}{W_d} \times 100 \qquad \text{.....(3.10)}$$

MC, % (db) = Moisture content, per cent (dry basis)

W_w= Amount of water evaporated, g

W_d= Dry matter

3.2.3 Equilibrium moisture content (EMC)

The equilibrium moisture content of each sample was taken at one per cent less than the final moisture content (Tiwari and Pandey, 2010). The final moisture content was taken when there remained almost constant mass of the sample with respect to time during experimentation.

3.2.4 Drying rate

The drying rate in terms of gram of water evaporated per gram of dry matter per minute was determined using the following equation (Abano *et al.*, 2011).

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad \text{....(3.11)}$$

Where, M_{t+dt} is the moisture content (gram of water evaporated/ gram of dry matter) at t+dt, and t is the drying time (min).

3.2.5 Moisture Ratio (MR)

Moisture ratio of the sample during drying was expressed by the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad \text{....(3.12)}$$

Where,

M_t =Moisture content at any time,t, % (d.b)

M_o= Initial moisture content, % (d.b.)

M_e= Equilibrium moisture content, % (d.b.)

It is more comprehensive parameter as it includes initial moisture content and equilibrium moisture content at any instant.

3.2.6 Modeling of drying characteristics

The drying curves of vegetable seeds were prepared by plotting moisture content (d.b.) at any instant versus drying time. Drying rate curves were also prepared by plotting moisture evaporated in gram per gram of dry matter per minute versus drying time. The drying kinetics of the three vegetable seeds was expressed in terms of empirical models. The experimental data obtained at different temperatures (30, 35 and 40^{o}C) were plotted in the form of dimensionless moisture ratio (MR) vs time. Different empirical drying models were employed to select the best one for the drying kinetics of vegetable seeds, Table 3.3. The drying rate was determined for different sets of experiments and all replications.

Non-linear regression analysis was performed to find the model constants. The expected and predicted values of MR were used to find the statistical parameters. The statistical parameters to determine the goodness of fit of the models were correlation coefficient (R^2), root mean square error (RMSE), standard error of estimate (SEE) and reduced chi-square ($\chi 2$). The highest R^2 and lowest value of χ^2, SEE and RMSE were used to determine the goodness of fit. (Togrul and Pehlivan, 2003; Sandeepa *et al.,* 2013; Cantu-Lozan *et al.,* 2013). The parameters were determined using the following formulas.

Table 3.3 Different drying kinetics models selected for vegetable seeds

Sl. No.	Model name	Model Equation	Model Characteristics
1	Newton	MR= exp(-kt)	Lewis or exponential model, simplest model, single model constant.
2	Page	MR= exp(-kt^n)	Modified Lewis model, two model constants.
3	Modified Page	MR= exp(-$(kt)^n$)	Two model constant,
4	Henderson and Pabis	MR= a exp(-kt)	General solution of Fick's second law of diffusion, simple model with two model constant
5	Logarithmic	MR= a exp(-kt)+c	Modified form of the Henderson and Pabis, Also asymptotic model, three model constant.
6	Two term exponential	MR= a exp(-kt) + b exp(-kt)	Second term general solution of the Fick's second law of diffusion, 2 model constants. The first term describes the last part of the drying process, while the second term describes the beginning of the drying process.
7	Wang and Singh	MR=1+at+bt^2	Developed for the intermittent drying of rough rice

(Togrul and Pehlivan, 2003; Onwude *et al.,* 2016)

$$\chi^2 = \frac{\Sigma_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp,i}} - \mathrm{MR}_{\mathrm{pre,i}})^2}{\mathrm{N - n}} \qquad \text{...(3.13)}$$

$$\mathrm{SEE} = \frac{1}{\mathrm{N}}\Sigma_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}}) \qquad \text{...(3.14)}$$

$$\mathrm{RMSE} = [\frac{1}{\mathrm{N}}\Sigma_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2]^{\frac{1}{2}} \qquad \text{.....(3.15)}$$

Observation on drying pattern of all the three vegetable seeds, as obtained in different set of experiments, were fitted to selected drying kinetics models, Table 3.3.

The patterns obtained were studies to select the best model to represent drying pattern of three selected vegetable seeds.

3.3 Determination of seed quality parameters

The quality parameters of the seeds such as germination percentage, vigour, seed health, electrical conductivity were studied at different temperature and moisture content. The temperature and initial moisture content were optimized based on the seed quality parameters. The optimized value was used for the design of the dryer.

3.3.1 Plan of Experiment

As quality of seed after passing through drying process may get deteriorated due to various factors, it was planned to conduct experiments on different quality parameters like germination percentage, vigor, seed health, electrical conductivity as per the plan of experiment, Table 3.4.

3.3.2 Experimental procedure

Moistened samples of all the vegetable seeds weighing 5±0.1g each were dried at constant temperature of 30, 35, 40ºC in convective hot air oven dryer with control temperature. The samples were dried up to a safe moisture level of 8±1% w.b. of all the three vegetable seeds at different levels of temperature. The reductions in moisture were recorded for every 15 minutes until it came to almost constant value.

Table 3.4 Plan of experiment for determination of seed quality parameters

Sl. No.	variables	Levels	Parameters
1.	Temperature	30, 35,40 ºC	Germination percentage, Vigor, Seed health, Electrical conductivity
2.	Type of seeds	Onion, carrot and tomato	
3.	Initial Moisture content	16 , 14 and 12% (w.b)	
	Experimental design= RSM, CCD design		

3.3.3 Moisture content (MC)

Moisture content of the selected vegetable seeds was determined using ISTA (2015) methods. The mass of the samples were taken according to the size of the moisture box. Sample of 4.5±0.5g can be taken for the box having diameter greater than 5cm and less than 8cm, whereas that in moisture box with diameter greater than or equal to 8cm, 10.0±1.0g sample mass were taken for the study. The temperature and time for determining moisture content of onion was 101ºC–105 °C (low temperature) and 17 ±1 hours whereas that of onion and carrot were 130–133 °C (high temperature) and 1 h ±3 min. The moisture content of the seed was determined by the following formula.

$$\text{MC (\% w.b.)} = \frac{\text{Amount of water evaporated}}{\text{Total mass of sample}} x 100 \qquad \text{...(3.16)}$$

3.3.4 Germination test

Seed germination percentage (SGP) was determined by top of paper method (ISTA, 2015). The seeds were allowed to germinated on top of one or more layers of paper which were placed into transparent boxes or Petri dishes (16 cm diameter), Plate 3.2 (a). The paper were soaked in distilled water and placed into the box. Each of 50 seeds were placed uniformly on the Whatman filter paper. The box after tightly closed to prevent evaporation, and was placed into the germination room. The observation on normal seedlings, abnormal seedlings, hard (unimbibed), and dead seeds were taken. The germination of onion, carrot and tomato was done as per the standard method. Table 3.5.

Table 3.5 Germination test methods for different vegetable seeds

Vegetables seeds	**First count (days)**	**Second count (days)**	**Incubation temperature (ºC)**
Onion	6^{th}	12^{th}	20-15
Carrot	7^{th}	14^{th}	20-30
Tomato	5^{th}	14^{th}	20-30

The seed germination percentage was calculated using the following formula, (Alhamdan *et al.,* 2011).

$$\text{SGP (\%)} = \frac{\text{Number of normal seedling}}{\text{Total number of seeds}} x 100 \qquad \text{..(3.17)}$$

A total of three replications were done and data on germination count was recorded.

3.3.5 Vigor test

Seed vigour test was determined as per the procedure mentioned in Afrakhteh *et al.*, 2013; Santorum *et al.*, 2013. A total of 50 seeds were placed uniformly on the top of soaked paper inside the petri dishes. Two dishes represented each treatment of four replications. After 12 days (onion) and 14 days (carrot and tomato) of incubation at 30˚C ± 1, ten seedlings were randomly selected from each dish to measure the following seedling vigor characters:

(1) Length (cm) of seedling, radicle and plumule, Plate 3.2 (b);

(2) Fresh weights of seedling, radicle and plumule (g).

The fresh ten seedlings were kept in a paper bags and weighed to take the fresh weight. It was then oven-dried at 60 °C for 24h to determine dry weight. Seedling vigor was calculated using the following formula given by Abdul-Baki and Anderson (1973):

Vigor index I = Germination% × total seedling length …..(3.18)

Vigor index II = Germination% × seedling dry weight ..... (3.19)

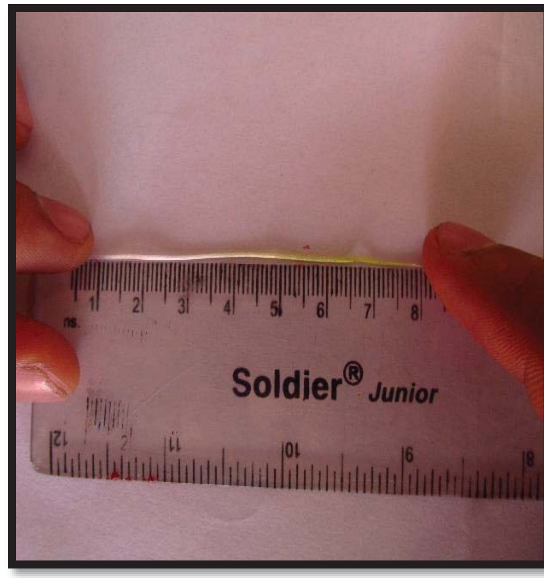
3.3.6 Seed health test

Infected seeds were identified by blotter test method (ISTA, 2015). Each three blotter paper (circular, e.g. Whatman No 1 or equivalent) were wetted with distilled water and placed into the sterile petri dishes, Plate 3.2 (c). A total of 25 seeds were kept in each plate. Taking reference by putting one seed at the center, the other remaining seeds were evenly placed on the wetted blotter paper with the help of forceps. The plate is then covered and placed in an incubation chamber for 9 days at 20 ± 2 °C with alternating 12 hour periods of darkness and light. Three replications were employed for each combination of treatments for all the crops. The samples were removed after the incubation period and examined for the infected seeds through naked eyes as well as through stereoscopic microscope. The observations were recorded as per standard protocol.

3.3.7 Electrical conductivity test

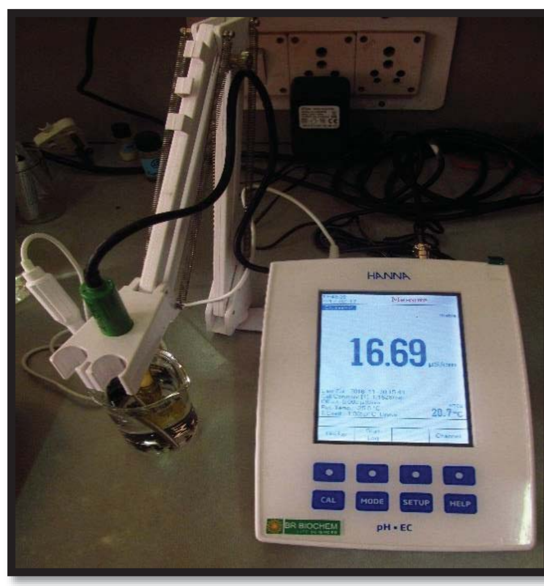
A total of 50 seeds for each vegetable crops were counted from each combination of treatments and soaked in 50 ml double distilled water at 20ºC and kept for 24 hours. The electrical conductivity meter was calibrated with double distilled

(a) Germination plate with onion seed



(b) Measurement of root and shoot length

(c) Petri plate for seed health test



(d) Electrical conductivity measurement

Plate 3.2. Apparatus used to determine seed quality parameters.

water at constant temperature. The soaked samples were stirred before taking the reading to distribute the leachate uniformly. The electrical conductivity of the samples was measured by electrical conductivity meter (cell constant-1.1528/cm, offset-0.000µS/cm) in terms of micro siemens per centimeter (µS/cm), Plate 3.2 (d). (Maryam and Oskouie, 2011; Sørensen *et al.,* 1996; ISTA, 2015).

3.4 Design of dryer and its components

A dryer was designed for uniform drying of vegetable seeds, namely, onion, carrot and tomato. It was powered entirely by the solar energy source using both thermal and electrical effects. The thermal power was obtained through solar water heater to heat up the air through heat exchanger whereas electrical power was obtained from solar photovoltaic cell to operate the fan and pump. The dryer consisted of drying chamber, water heating unit, heat transfer unit, air handling and distribution unit, power supply and temperature controls unit (Fig.3.1).

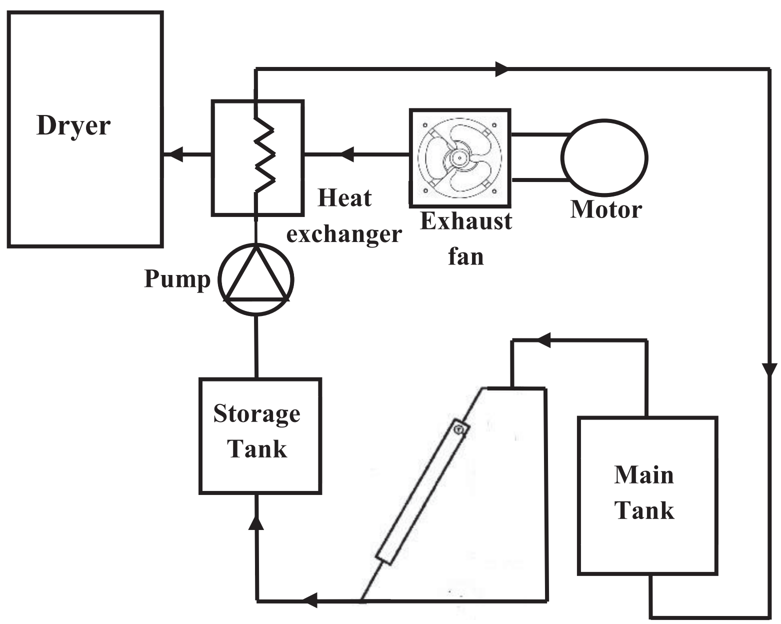


Fig. 3.1 Schematic diagram of the developed dryer

3.4.1 Design considerations

Design means intent or purpose. The acceptability of any designed products depends on its reliability, energy and economic sources of its operation. Reliability is basically probability that product performs the intended job in intended working environment for intended period without fail. Thus, a good design should in corporate necessary factors which impart the deserved qualities to the product. The design considerations for the dryer in present study are as given below:

1. **Harvesting period of the selected vegetable seeds**

   Harvesting period decide the environmental conditions such as temperature, relative humidity, sunshine hours, solar radiation and wind speed. It influences the selection of total drying time for solar dryer.

2. **Amount of moisture to be removed**

   The moisture present in seed during harvesting is generally high. It has to be brought down to a safe moisture level for storage which requires drying. The amount of moisture to be removed from a given quantity of seed decides the energy required to supply for drying.

3. **Quantity of air needed for drying**

   Forced convection dryer provides better and uniform drying through continuous removal of moist air resulting in faster drying rate. Therefore, it was necessary to evaluate the amount of air required to supply by fan during drying process.

4. **Total solar energy received in the region**

   The energy required to dry the seeds by a solar dryer depends on the amount of moisture to be removed and the solar energy available in the region. The available solar energy should be sufficient enough to power the system, both electrical and thermal, to be effective for drying.

5. **Allowable temperature for drying seeds**

   Vegetable seeds are delicate organisms and need to be processed carefully without losing its quality. Drying is one of the sensitive unit operations required to reduce the moisture content at safe level for storage. High temperature of drying may results in deterioration of seed quality. Therefore, it is important to understand the permissible temperature limits for drying vegetable seeds. Thus, kinetics of vegetable seed drying becomes important.

3.4.2 Determination of design values

Drying process basically involves removal of moisture from crop materials i.e. vegetable seeds in present case. So, the design involves determination of the amount of moisture to be removed which in turn, would depend on type of vegetable seeds, moisture at the time of harvest and amount of moisture to be dried at a given time.

This, in turn would help in deciding capacity of the dryer of this study. Next important aspect is quantity of heat required to obtain the desired level of seed drying. The quantity of heat required would be determined by the mass of the seed to be dried, specific heat of the seed, and amount of heat required to vaporize the moisture from the product i.e. vegetable seeds. Proper selection and assembling of different units such as water heating unit, heat transfer unit, air distribution unit, photovoltaic power supply and temperature control unit are important for efficient operation of the dryer. Also, for design of the drying chamber the following assumptions were made (Table 3.6).

Table 3.6 Assumptions for the design of dryer

Sl. No.	Parameters		Standard values and required assumptions
1.	Initial moisture content of seeds	m_i	20 % w.b.
2	Final moisture content of seeds	m_f	8% w.b.
3.	Initial mass of the product to be dried	m_p	3 kg, capacity of the designed dryer
4.	Ambient temperature during harvest (April)	t_a	33°C
5.	Initial temperature of product	t_p	26°C
6.	Specific heat of air	C_{pa}	1.005 kJ/kg K
7.	Density of air	ρ_a	1.225 kg/m^3
8	Length of inside chamber	L_i	0.6 m
9	Width of inside chamber	W_i	0.3m
10	Height of inside chamber	H_i	0.76m
11	Density of seed	ρ_s	500 kg/m^3

3.4.3 Design Calculations

a) The amount of moisture to be removed from the product, m_w (kg) was calculated using the following equation (Tonui *et al.* 2014, Ogheneruona and Yusuf, 2011). The initial moisture content was taken considering the maximum moisture content of vegetable seeds at the time of harvest.

$$m_w = m_p \frac{(m_i - m_f)}{(100 - m_f)} \quad \ldots(3.20)$$

So,

m_w =0.4kg

Thus, the moisture to be removed for 3 kg of vegetable seed was found to be 0.4 kg.

b) The quantity of heat required to remove the moisture content

$$Q=m_p c_p \Delta T_p+m_w h_{fg} \quad \ldots..(3.21)$$

C_p= Specific heat of product (Singh and Sahay, 2004)

$$c_p = (\frac{m_w}{100}) \text{ x } c_w + \frac{(100 - m_w)}{100} \text{ x } c_d \quad \ldots.(3.22)$$

c_{pw}= specific heat of water (4.18 kJ/kgK)

c_{pd}= specific heat of dry matter (1.463-1.881 kJ/kgK)

ΔT_p= change in temperature before and after heating (ºC), t_a-t_p

Therefore, C_p=2.341kJ/kgK

h_{fg}=the latent heat of evaporation kJ/kg. The amount of heat needed is the function of temperature and moisture content of crop. The latent heat of vaporization can be calculated by, (Ogheneruona and Yusuf, 2011; Dasin *et al.,* 2015)

$$h_{fg} = 4.186(597 – 0.56(t_{pr}+273) \quad \ldots\ldots(3.23)$$

wheret_{pr} [ºC] is the product temperature

=1800kJ

Therefore, Q= 770kJ

Thus, the amount of heat energy required to remove 0.4 kg of moisture was worked out to be 770 kilo joule.

3.4.4 Design of drying chamber

Drying chamber is the most important unit of a dryer. It accommodates different size of trays in multilayer to facilitate thin layer drying in uniform manner and at expeditious rate. The design factors of drying chamber included its size, number of trays, space between two trays, number of holes for air inlet, materials for insulation

Plate 3.3. The fabricated dryer for vegetable seeds

and size of vent and air passage. The designed capacity of the dryer was kept as 3.0 kilogram. The size of the dryer and energy required for the operation was decided according to moisture to be removed to bring down the moisture content from the harvesting moisture content to the safe storage level. The dryer was fabricated and had two chambers i.e. inner and outer, Plate 3.3. The inner chamber was made for mounting the tray inside in different layers. Between inner and outside chamber, there was a provision for passage of hot air. Insulation was also provided in this space to prevent heat lost to the surrounding. Insulation material are attached with the outside chamber and fixed with polycarbonate sheet. Materials of construction for the drying chamber were selected based on the technical and economics aspect (Table 3.7).

Table 3.7 Selection of material for fabrication of dryer.

Sl. No.	Chamber units	Material of construction	Reason of selection
1	Body of inside and outside chamber	Mild steel	Good strength, weldability and machinability.
2	Insulation	Glass wool	Low thermal conductivity (0.035W/mK), high heat resistance and cheap.
3	Perforated Tray	Stainless steel (SS304)	Weldability, product use (seeds).
4.	Fixing of insulation	Polycarbonate sheet	High strength, light weight, heat resistance.

Number of trays

Number of trays were provided based on the capacity and permissible thickness of the seeds layer to be dried in thin layer drying i.e. 5.0 mm for seeds. Perforated tray was selected to allow easy flow of the air to the seed mass. The tray holes were decided based on the shape and size of the vegetables seeds studied. Area of tray was kept to fit inside chamber i.e. ($0.6m x 0.3m = 0.18m^2$). Considering the thickness of layer and 2.0 cm clearance for handling, the height of the tray was kept as 2.5 centimetre. The number of tray was calculated using the following formula:

Number of tray = m_p / (Area of one tray x thickness of seed layer x ρ_s)

=6.66 = 7(approx.)

Tray to tray gap = H_i/ number of trays =0.76 m/7= 9.5cm.

Therefore, total number of chamber = (number of tray +1) = 8

a) **Number of holes for air flow**

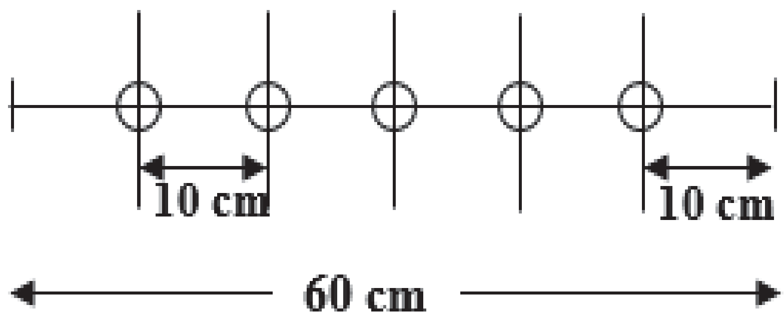


Fig. 3.2. Dividing the inner chamber length into equal parts

Holes were provided on both sides of the inner chamber for the hot air to pass through tray and consequently to the seeds. The total length of the inner chamber i.e. 0.6m was divided into 6 equal parts making 5.0 total number of holes at 10 cm apart (Fig. 3.2). Holes were made 2.0 mm above each tray on both sides so as to provide quick and easy contact with the seeds.

b) **Air vent/ air passage**

Air gap between inside and outside chamber was provided for hot air to pass to the holes of inside chamber. It was suggested that for hot climate passive solar dryers, a gap of 5.0 cm should be created as air vent (inlet) and air passage (Raju *et al.*, 2013).

c) **Insulation**

Insulation using glass wool was incooperated to prevent heat loss. The thickness of insulation was kept 4.0 cm on both walls where hot air directly came in contact with inside chamber; whereas thickness was kept 3.0 cm on roof and floor of the chamber. Polycarbonate sheet having 1.0 cm thickness was used to fix the insulation to the outside chamber (Plate 3.3).

d) Dimension of outside chamber

The dimensions of the outside chamber was determined combining by adding together the thickness of insulation, air passage gap to dimension of inside chamber. Thus, the dimensions of the outside chamber was determined as follows.

Length, L= Li +0.1m=(0.6+0.1)=0.7m

Height, H= (0.76+0.03+0.03)= 0.82m

Width, W=[0.3+(0.04+0.04+0.01)x2]=0.5m

An insulated door was provided to prevent heat loss and to make the chamber air-tight. Rubber gasket was mounted so as to prevent any leakage of air during drying process.

Thus, the overall dimension of the outside chamber was (0.7x0.5x0.82) meter.

3.4.5 Air handling and distribution unit

The dryer was operated with forced convection process. An air handling and distribution unit was provided to supply hot air from the source through fan to inside the drying chamber. The main parts of this unit included fan and air duct. The airflow was divided into two equal parts from the source towards the air-vent. This distribution unit was mounted on both sides of the bottom of the chamber. Assuming a width to height ratio of 1:3, the height of air vent was taken as 15 cm as the width of was 5 cm. This formed a rectangular section for air passage. These two air passage were again joined forming smaller opening end of hopper (Fig. 3.3). The other side of the hopper was made to accommodate the heat exchanger inside it. The hopper was made from polycarbonate sheet whereas the air duct was made from galvanized iron sheet because of strength, weldability and light weight. Air handling unit was designed in such a way that there was minimum passage for the hot air to pass so as to minimize heat loss. The dimensions of the air distribution units are given below.

a) Hopper size:

Smaller openings end= (12x15) cm

Larger opening end = (35x 40) cm [depending on heat exchanger size]

Length of the hopper = 40 cm [Assuming width and length ratio as 1:1]

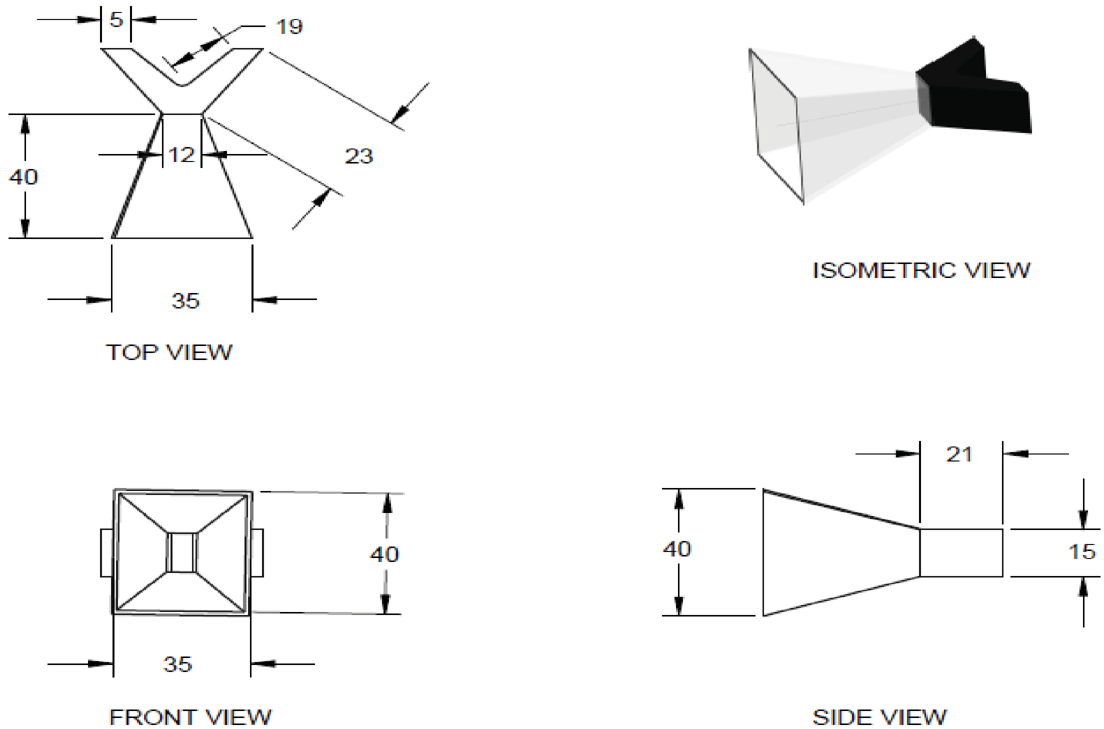


Fig. 3.3. Schematic diagram of air handling and distribution unit

b) Air duct

Air duct was distributed into two sections from the smaller end opening of the hopper. The dimensions of air duct were 19 cm x 5 cm x 15 cm each for both sides. The distance between the hopper and the dryer was kept 13 centimetres.

A fan was provided to force the air to the drying chamber through air duct. The selection of the fan was done depending upon the air-flow required to dry the seeds. The mass of the air which was required to dry the given amount of seed was determined using basic energy balance equation

$$Q=m_a c_{pa} \Delta T, \text{ [from eqn. (3.21)]}$$

Where, m_a= mass of air required, kg

$\Delta T= t_h- t_a=1$[considering minimum change in temperature to obtain maximum flow]

Therefore,

m_a= 766 kg=770kg (approx.)

ma x $(1/\rho_a)$ = 943.25m^3=945m^3(approx.)

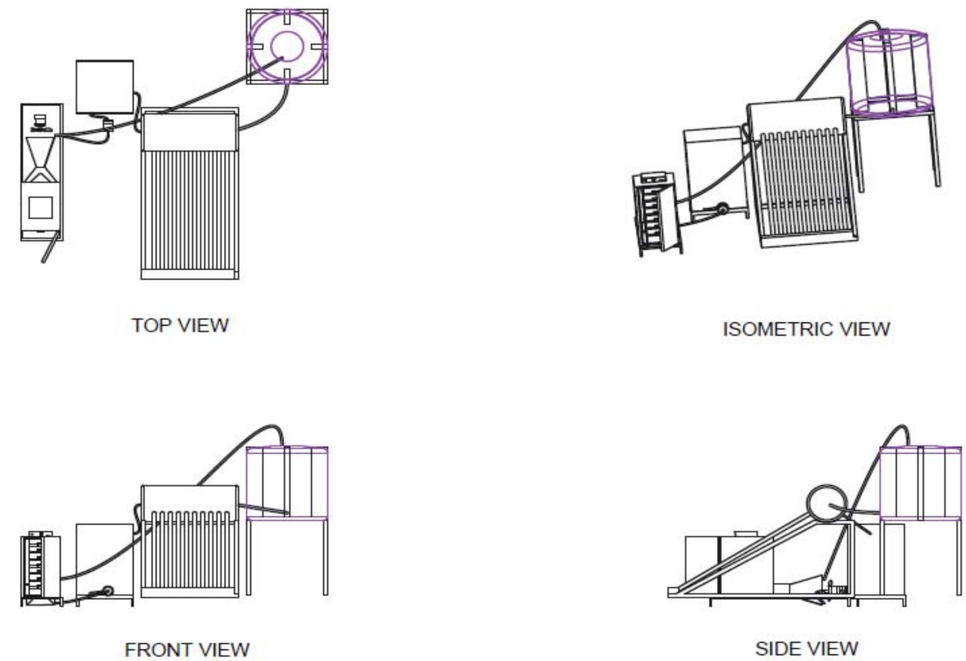


Fig: 3.4. Schematic Diagram of different units of automated solar dryer

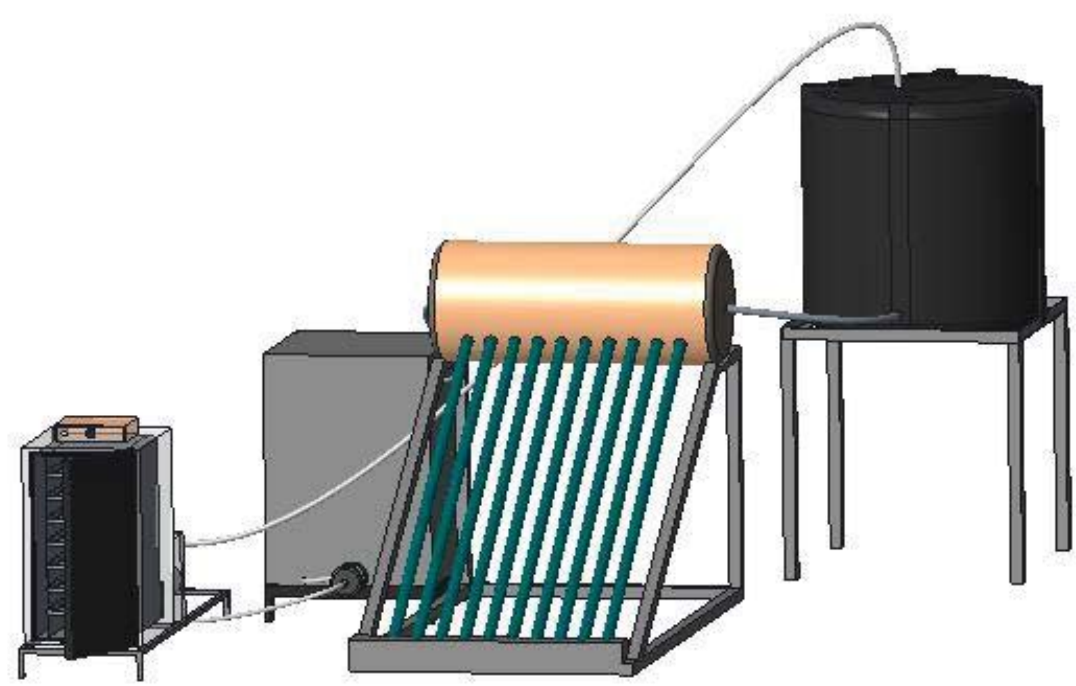


Fig: 3.5. Isometric view of developed solar dryer system

Assuming the time required to dry seeds from 20% w.b. moisture content to 8% w.b. is 7 hours, the flow rate of the air required was 0.04 m^3/s. The size of fan was selected on the basis of matching capacity of the pump and heat exchanger. A fan of 15" size was selected and having 78 watt rating operated on 220 V wherein the fan speed was 920 rpm. Figure 3.4 and Figure 3.5 showed the schematic diagram and isometric view of the developed solar dryer.

3.4.6 Heat transfer unit

The developed dryer was designed to obtain hot air from hot water through heat exchanger. Hot water storage system was provided to facilitate the storage of sensible heat. This system enables the use of indirect solar thermal energy by storing hot water. This helped in using the thermal energy when there was cloudy or less sunshine. This system included pump, heat exchanger and pipe fittings.

i) Heat exchanger: A fins and tube heat exchanger was selected to transfer the heat between the hot water and ambient air. The capacity of the heat exchanger was decided according to the amount of energy required to dry the seed i.e. 770 kJ. Considering 7 hours of drying time, the amount of refrigeration required was 0.2 tons of refrigeration [1TR=3.5kW]. The commercially available capacity of fins and tube heat exchanger was 0.5TR. The dimensions of the selected heat exchanger were 35 cm x31 cm x 4 cm with 11 numbers of tubes with two runs. The tube having diameter of 1.0 cm was made from copper whereas the fins was made of aluminium.

ii) Pump: A centrifugal pump was attached to the exit of hot water storage tank and supplies the hot water into the heat exchanger. As the heat transfer was less, minimum available pump horse power was selected to circulate the hot water into the heat exchanger.

iii) Pipe fittings: Hot water flexible pipe (PVC) was used to transfer the hot water between storage tank and pump. A return pipe was used between the exit of heat exchanger and cold water storage tank.

3.4.7 Water heating unit

Water heating unit consisted of hot water storage tank, solar water heater and cold water storage tank. It was provided to store thermal energy in the form of sensible heat. The water was heated through solar water heater and stored in hot water storage tank. There was continuous supply of cold water to the solar water heater.

i) Hot water storage tank: Hot water storage tank made of galvanized iron was provided for thermal storage. As the hot water requirement to raise the temperature to desire level was 185 kg, the capacity of the tank selected was 250 litres (61 cm x 61 cm x 100 cm) by giving 30 % clearance so that sufficient air space was provided inside the tank. Insulation was provided with glass wool (5 cm) in between inner and outside tank to prevent heat loss from the hot water. The inlet of hot water tank was connected through the exit of solar water heater.

ii) Solar water heater: Solar water heater having capacity of 200 L/day with 10 evacuating tubes was chosen based on the hot water requirement to raise the temperature i.e. 185 kilogram (Make-mega power solar).

iii) Cold water storage tank: A higher capacity of 300L of cold water storage tank was chosen for continuous supply of cold water to the solar water heater.

3.4.8 Power supply and control units

Drying process required energy to remove moisture from seed mass. The energy required to raise the temperature was achieved through solar thermal energy that was stored in water in the form of sensible heat. A heat exchanger was provided to transfer heat from hot water to the ambient air resulting in the rise of air temperature. A fan was provided to blow the heated air to the drying chamber. A temperature control unit was attached for precise control of temperature inside the drying chamber. This needed power supply for fan, pump and control units for operation of the dryer. The power was supplied from the solar photovoltaic array. Thus, the selection of the solar photovoltaic panel was made according to power required by fan, pump and control units.

i) Power supply: Power supply unit consisted of solar photovoltaic panel (Microtek), maximum power point tracker (MPPT, 5A), storage battery (12 V) and inverter. Solar panels were connected in parallel to obtain the required maximum current. The solar photovoltaic array was connected to MPPT where the higher voltage DC output from solar panels was optimized to lower voltage needed to charge battery. The battery was connected to an inverter which converted direct current (DC) to alternating current (AC) required to run the fan, pump and control unit.

ii) Control units: A control unit was designed which consisted of digital temperature indicator cum controller that regulated the supply of heat depending on the temperature inside the chamber. A thermocouple (PT 100) was attached inside the chamber which was connected with 16A solid state relay (SSR). The thermocouple acted as load which directed the SSR and regulated ON and OFF of the motor. When the temperature exceeded the set value, the motor which supplied hot water will cut off whereas if it lowered down to less than the set value, the motor started functioning. It was fitted with main switch, fan switch with regulator, motor switch and temperature control (Fig.3.6, Plate 3.4). The relay worked on single phase 220V AC and 50 Hertz.

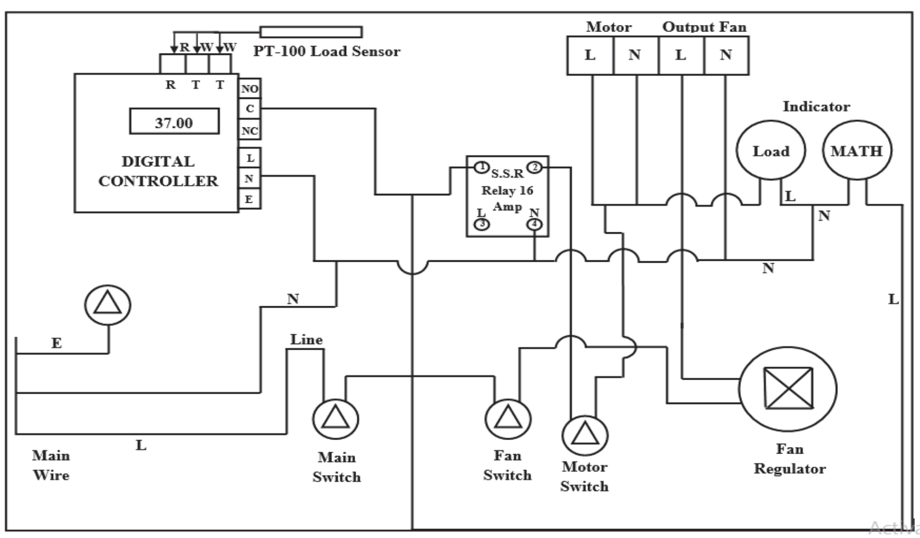


Fig. 3.6 Circuit diagram of the temperature controller

3.5 Performance evaluation and cost estimation

The performance and efficiency of the developed dryer was evaluated. Efficiency was determined based on the energy input and energy utilized by the dryer. The performance was evaluated at different loads. All the tray were filled with given mass of the seeds. Initial weight of the seeds on each tray were taken and measured the difference in moisture by taking weight at every 1.0 hour interval (Plate 3.5).

Plate 3.4. Temperature controller with fan speed control.

Plate 3.5. Measurement of seed mass at one hour interval

Drying kinetics was also determined to know the drying behavior of different seeds at different loads in actual drying process by the developed dryer.

3.5.1 Efficiency of the developed dryer

The overall thermal efficiency of solar dryer can be defined as the ratio of energy required to evaporate the water plus sensible heat require to raise the temperature of the product to the useful energy gained by the solar dryer.

$$\eta_{dryer} = \frac{m_p c_p \Delta T_p + m_w h_{fg}}{Q_a} \quad \text{......(29)}$$

Where, $Q_a = m_a c_{pa} \Delta T_a$

M_a= mass flow rate of air

3.5.2 Performance evaluation of the dryer

The performance of the developed dryer was evaluated at three different loads i.e. 3kg, 2kg and 1kg, respectively, for all the selected vegetable seeds. The seeds were dried at optimized temperature for each seeds. The responses studied were drying kinetics and seed quality parameters including germination percentage, infected seeds, electrical conductivity and vigor. The time required to bring the safe moisture level for each loading conditions were obtained from dying kinetics. Samples were taken from each load and tested for seed quality as per the plan of experiment (Table 3.8).

Table 3.8 Plan of experiment for evaluation of the developed dryer

Sl. No.	Parameters	Levels	Responses studied
1	Load	1, 2 and 3 kg	• Drying kinetics • Seed quality parameters (germination percentage, number of infected seeds, vigor index-I and II and electrical conductivity)
2	Type of seeds	Onion, carrot and tomato	
	Replications=3 Type of seeds=3 Number of experimental runs=3x3x3=27		

3.5.3 Total cost

The total cost of the dryer and its operational units was determined based on fixed cost and variable cost. The following variables were considered in determining the cost of operation.

A) Fixed Cost

i) Manufacturing cost of complete setup

ii) Depreciation

iii) Interest

iv) Insurance and taxes

B) Variable cost

i) Repair and maintenance

The total cost of the developed dryer was determined as the sum of fixed and variable cost. The total cost of operation of the dryer per hour was evaluated, **Annexure (IV)**. The breakeven point (BEP) and Pay Back Period (PBP) were also computed for the dryer.

i) Breakeven point

The breakeven point is the point at which the gains is equal to the losses. A breakeven point defines when an investment will generate a positive return. There is no profit made or loss incurred at the breakeven point. In fact, the breakeven point is the lower limit of profit when prices are set and margins are determined.

$$BEP = FC/(CF - C) \qquad \text{....(30)}$$

Where, BEP= Breakeven point, h/year

FC= Annual fixed cost, Rs/year

CF= custom fee, Rs/h

C= operating cost, Rs/h

CF=1.25x(C+0.25C)

ii) Payback period

The payback period is defined as the length of time required to recover an investment through cash flows generated by the investment.

$$PBP=IC/ANP \quad \text{.....(31)}$$

Where, PBP= Payback period, year

IC= initial cost of the dryer, Rs

ANP= (CF-C)AU

Where, ANP= Annual net profit

AU= Annual utility, h/ year

AU=AAx EC

Where, AA=Average overall use, h/ year

EC= effective capacity of the dryer, kg/ hr

3.6 Statistical analysis for different experiments

Statistical analysis was conducted for different experiments as per the selected experimental designed required to develop the dryer. Different designs and statistical software were used for different experiments.

1) In determining engineering properties of seeds at different moisture levels, full factorial design was employed for the study. A one-way analysis of variance test (ANOVA) was carried out using the software SAS (version 9.3) to examine the effect of moisture content on engineering properties of selected vegetable seeds i.e. carrot, onion and tomato with the proposed experimental design. The mean values and standard error for all the properties were evaluated using the MS Excel 2010.
2) Non-linear regression analysis using NLREG software was conducted in the study of drying kinetics and found the constant values of the drying models. The best model was selected depending on statistical parameters i.e correlation coefficient (R^2), the root mean square error (RMSE), Standard error (SE) and the reduced chi-square (χ^2). The highest R^2, lowest χ^2, ME and RMSE were used to determine the goodness of fit.

3) Design Experts program (version 10.0.0) of the STAT-EASE software was used for simultaneous optimisation of the responses i.e. seed quality parameters with respect to temperature and moisture content.

Chapter 4

RESULTS

This study was done to develop solar operated vegetable seed dryer with automated temperature control system to obtain uniform and safe drying of the delicate seeds of commonly used vegetable like onion, carrot and tomato. The important feature of the dryer was to provide automatic control of temperature of the drying air. Considering limitation and cost of fossil fuels and availability of solar energy, the dryer was operated fully by taking both thermal and electrical power of solar energy. This may help the farmers in saving energy as well as in augmenting the ethos of increased use of solar energy in agricultural purposes.

Engineering properties of three selected vegetable seed e.g. onion, carrot and tomato were determined to understand the ranges of designed values of certain parameters of dryer. The dryer was designed and fabricated after determining the design values of its component. Engineering properties and seed quality parameters with respect to temperature and moisture content were evaluated. Drying of seeds was conducted in laboratory and optimized temperature was obtained based on the seed quality parameters. Drying kinetics was also studied to find the drying behaviour of the seed. The optimized temperature was set and best drying kinetics models was selected for the developed dryer. The performance of the dryer was examined at different load of all the selected vegetable seeds. The efficiency of the dryer and its sub-units were evaluated. The cost economics of the dryer was estimated including its breakeven point and payback period. The results of the study are presented in this chapter.

4.1 Effect of moisture content on engineering properties of vegetable seeds

The effect of moisture content on bulk density, true density, terminal velocity, test weight, sphericity, surface area, geometric mean diameter, arithmetic mean diameter, porosity and angle of repose and coefficient of friction were evaluated in terms of their mean value and standard error (Table 4.1 and Table 4.3). The linear regression models were developed for each property by considering the highest coefficient of determination and least associated standard error (Table 4.2 and Table 4.4). The effects of moisture content on different properties are presented below.

Bulk density

The bulk density of carrot, onion and tomato seed were observed as 0.32±0.01 g/cm^3, 0.45±0.01 g/cm^3, 0.289±0.01 g/cm^3 respectively at 20±1% w.b. The same was 0.43±0.04 g/cm^3, 0.47±0.003 g/cm^3, 0.30±0.01 g/cm^3 at storage moisture content of 8±1 % w.b., respectively in the same order. The decrease pattern in bulk density with increase in m.c. at 8±1 % w.b., 12±1 % w.b., 16±1 % w.b. and 20±1 % w.b. level of moisture followed linear trend indicating linear relationship between moisture content and bulk density. Thus, the bulk density of all the selected vegetable seeds increased as the moisture content decreased (Table 4.1). Similar decreasing trend in bulk density has been reported by Altuntaş and Demirtola, (2007) for legumes seeds, Garnayak *et al.,* (2008) for Jatropha seed, Singh *et al.,* (2010) for millet and Ilori *et al.* (2016) for amaranthus. The regression models for bulk density and moisture content was developed with an aim of analyzing its effect on bulk density. The regression model was found significant at $p < 0.05$ for all the seeds. The coefficient of determination was observed highest for carrot (R^2=0.96) whereas for onion and tomato it was the same, R^2=0.931, (Table 4.2).

True density

True density of carrot, onion and tomato seeds were observed as 1.23±0.12 g/cm^3, 1.14±0.05 g/cm^3, and 1.03±0.06 g/cm^3 at 20±1% w.b. A decrease of 14.9 %, 0.9 % and 10.7 % in true density was observed where moisture content of the seeds of carrot onion and tomato was brought down from 20% to 8% wet basis. True density of carrot seed decreased significantly from 1.23±0.12 to 1.07±0.05 g/cm^3 as the moisture content decreased from 20.73% to 8.15% wet basis. Similar trend was observed in green wheat (Mahasneh *et al.,* 2007) and hemp seed (Sacilik *et al.*, 2003).Regression analysis showed linear relationship and found significant ($p < 0.05$) with coefficient of determination 0.96 (Table 4.2). But the true density of onion and tomato was found to decrease by 6.15% and 9.65% when the moisture content increases by 58.6% and 60.48% respectively (Table 4.1). The coefficient of determination for onion and tomato were 0.997 and 0.935 respectively.

Terminal Velocity

Terminal velocity gave a measure of aero dynamic properties of vegetable seed. The terminal velocity of carrot, onion and tomato at harvesting moisture content

(20±1 % w.b) were found as 2.52±0.09 m/s, 2.63±0.08 m/s, 2.10±0.03 m/s whereas, terminal velocity at safe storage moisture level of 8±1% w.b, were 1.81±0.24m/s, 1.92±0.4m/s and 1.96±0.05 m/s, respectively. It increased significantly by 53.17%, 27% and 6.7% with the increase in moisture content by 60.68 %, 58.6 % and 60.48 per cent (Table 4.1). The regression models were found significant ($p<0.05$) with coefficient of determination (R^2) 0.96, 0.97 and 0.96 respectively for carrot, onion and tomato (Table 4.2). Similar trend of increase in terminal velocity with increase in moisture content was observed in cumin seed (Singh and Goswami, 1996) and hemp seed (Sacilik *et al.* 2003).

Test weight

The test weight (1000 seed weight) for all the three vegetable seeds increased significantly with the increase in moisture content. The test weight of carrot, onion and tomato seed decreased from 3.01±0.21 to 2.04±0.22 g, 4.20±0.19 to 3.61±0.23g and 3.20±0.12 to 3.09±0.17g with decrease in moisture content from 20.73 to 8.15% (w.b), 20.88% to 8.65 (w.b) and 20.57 % to 8.15%,w.b. respectively. The regression models were found significant ($p< 0.05$) for all the selected seeds with coefficient of determination (R^2) 0.959 for carrot, 0.970 for onion and 0.957 for tomato, respectively (Table 4.2).

Geometric properties

- **Sphericity**

Sphericity was used as a measure of shape of the seeds. In general, with the increased in moisture content sphericity increase indicating the swelling of seed due to moisture absorption. The sphericity for carrot, onion and tomato seeds was observed as 0.42±0.01, 0.69±0.01, 0.47±0.01 respectively at moisture content of 20±1% w.b. and 0.45±0.03, 0.70±0.0.2 and 0.50±0.01 respectively at 8±1% wet basis. Sphericity decreased by 6.7%, 1.4% and 6% with the increase in moisture content by 60.68%, 58.6% and 60.48% for carrot, onion and tomato respectively (Table 4.1). Regression analysis showed linear relationship and found significant ($p< 0.05$) for all the selected crops seeds. The coefficient of determination (R^2) for carrot, onion and tomato were 0.96, 0.94 and 0.91 respectively. Similar trends of decrease have been reported by Nimkar and Chattopadhyay (2001) for green gram, Baryeh and Mangope (2002) for pigeon pea.

- **Surface area**

The surface area for all the selected vegetable seeds increased significantly as the moisture content increased. The surface area of carrot, onion and tomato increased from 7.10±0.22 to 8.34±0.24 m^2, 13.39±0.28 to 15.47±0.36 m^2 and 7.59±0.56 to 10.10±0.35m^2 with increase in moisture content from 8.15 to 20.73 % (w.b), 8.65 to 20.88% (w.b) and 8.15 to 20.57 % (w.b.), respectively (Table 1). Regression models were found significant ($p<0.05$) for all the selected crop seeds. The coefficient of determination (R^2) for carrot, onion and tomato are 0.93, 0.98 and 0.96, respectively (Table 4.2). Similar trends of increase have been reported by Sacilik *et al.* (2003) for hemp seed and Altuntas *et al.* (2005) for fenugreek.

- **Arithmetic mean diameter and geometric mean diameter**

Regression models showed the significant effect of moisture content on arithmetic mean diameter and geometric mean diameter for all the crop seeds ($p<0.05$) (Table 4.2). Arithmetic mean diameter of carrot, onion and tomato increased by 7%, 6.5% and 10.9% whereas geometric mean diameter increased by 7.4%, 6.8% and 13.4% with the increased in moisture content by 60.68%, 58.6% and 60.48% respectively, (Table 4.1). The coefficient of determination (R^2) for carrot, onion and tomato were 0.942, 0.950 and 0.977 for arithmetic mean diameter whereas that of geometric mean diameter were 0.970, 0.931 and 0.948, respectively. Similar results have been reported by Pandiselvam *et al.* (2014) for onion seed and Mollazade *et al.* (2009) for cumin.

Porosity

Porosity for carrot decreased from 73.82 to 60.32 % whereas that of onion and tomato increased from 49.76 to 59.95 % and 71.90 to 73.58 % with the decreased in moisture content from 20±1 % w.b to 8±1 % wet basis (Table 4.1). Regression analysis showed the positive correlation of moisture content and porosity for carrot whereas negative correlation for onion and tomato. The coefficient of determination (R^2) for carrot, onion and tomato were 0.930, 0.950 and 0.918 respectively. The decrease in trend was also observed in hemp (Sacilik *et al.,* 2003) and fenugreek (Gupta and Das 1997). Increasing trend was observed in soybean (Tavakoli *et al.* 2009).

Table 4.1. Engineering properties of carrot, onion and tomato seeds at different moisture levels

Moisture content (% wb)	**Bulk density** (g/cm^3)	**True density** (g/cm^3)	**Terminal velocity** (m/s)	**Test weight** (g)	**Sphericity**	**Surface area** (mm^2)	**GMD** (mm)	**AMD** (mm)	**Porosity** (%)	**AOR** (^{0})
Carrot seed										
8.15	0.43±0.04	1.07±0.05	1.81±0.24	2.04±0.22	0.45±0.03	7.10±0.22	1.50±0.21	1.87±0.24	60.32±1.52	33.79±0.51
12.01	0.38±0.02	1.12±0.06	2.12±0.12	2.16±0.10	0.44±0.01	7.15±0.20	1.50±0.03	1.91±0.07	66.55±1.86	34.32±0.17
16.37	0.35±0.02	1.14±0.06	2.40±0.12	2.58±0.10	0.43±0.01	7.86±0.20	1.57±0.03	1.93±0.07	69.60±1.63	34.94±0.17
20.73	0.32±0.01	1.23±0.12	2.52±0.09	3.01±0.21	0.42±0.01	8.34±0.24	1.62±0.03	2.01±0.08	73.82±1.68	36.03±0.50
Onion seed										
8.65	0.47±0.003	1.15±0.06	1.92±0.40	3.61±0.23	0.70±0.02	13.39±0.28	2.06±0.08	2.17±0.04	59.95±1.70	31.21±0.18
12.32	0.46±0.003	1.15±0.05	2.01±0.09	3.81±0.10	0.70±0.01	14.25±0.47	2.13±0.08	2.24±0.03	59.11±2.01	33.27±0.26
16.82	0.46±0.003	1.15±0.05	2.35±0.20	3.93±0.06	0.69±0.01	14.78±0.37	2.16±0.04	2.26±0.05	55.15±0.97	34.31±0.48
20.88	0.45±0.01	1.14±0.05	2.63±0.08	4.20±0.19	0.69±0.01	15.47±0.36	2.21±0.09	2.32±0.05	49.76±1.74	35.41±0.28
Tomato seed										
8.15	0.30±0.01	1.14±0.04	1.96±0.05	3.09±0.17	0.50±0.01	7.59±0.56	1.55±0.06	1.96±0.06	73.58±1.11	38.05±0.15
12.70	0.29±0.01	1.12±0.06	2.04±0.03	3.14±0.17	0.50±0.01	8.96±0.29	1.69±0.03	2.08±0.07	73.40±0.97	38.52±0.28
16.53	0.29±0.002	1.07±0.04	2.05±0.03	3.17±0.12	0.49±0.01	9.58±0.20	1.75±0.02	2.15±0.03	72.34±1.35	38.70±0.40
20.57	0.28±0.01	1.03±0.06	2.10±0.03	3.20±0.12	0.47±0.01	10.10±0.35	1.79±0.03	2.20±0.10	71.90±1.35	38.91±0.15

Values are mean±SE. GMD= geometric mean diameter, AMD=Arithmetic mean diameter, AOR= Angle of repose

Table 4.2. Regression model as a function of moisture content for different engineering properties of selected vegetable crop seeds

Sl. no	Property	Carrot seed			Onion seed			Tomato seed		
		Regression equation	R^2	P	Regression equation	R^2	P	Regression equation	R^2	P
1	Bulk density	-0.008x+0.483	0.960	0.020	-0.0014x+0.480	0.931	0.035	-0.00085x+0.3080	0.931	0.035
2	True density	0.0116x+0.974	0.960	0.040	-0.0007x+1.157	0.997	0.001	-0.00907x+1.221	0.935	0.033
3	Terminal Velocity	0.05716x+1.393	0.959	0.021	0.06052x+1.339	0.970	0.015	0.010215x+1.889	0.957	0.022
4	Test weight	0.07902x+1.32	0.962	0.019	0.0459x+3.211	0.977	0.012	0.008395+3.027	0.995	0.003
5	Sphericity	-0.00256x+0.470	0.962	0.018	-.000145x+0.717	0.938	0.031	-0.00244x+0.527	0.911	0.046
6	Surface area	0.1058x+6.099	0.934	0.033	0.1638x+12.066	0.984	0.008	0.199943x+6.160	0.957	0.022
7	G. Mean Dia	0.01088x+1.392	0.924	0.039	0.012x+1.963	0.973	0.014	0.018997x+1.420	0.948	0.026
8	A. Mean dia	0.011x+1.772	0.942	0.030	0.0114x+2.082	0.950	0.030	0.018953x+1.822	0.977	0.012
9	Porosity	1.03x+52.83	0.970	0.014	-.84388x+68.367	0.931	0.035	-0.14679x+74.933	0.918	0.042
10	Angle of repose	0.17477x+32.271	0.976	0.012	0.32897x+28.73	0.957	0.022	0.067697x+37.564	0.961	0.020

R^2= coeff. of determination , $P<0.05$= significant at 5% level of significance, $p<0.01$= significant at 1% level of significance.

Angle of repose

Angle of repose is the measure of angle with the horizontal surface at which the material will stand when piled. In general, the angle of repose increase with the increase in moisture content due to cohesive force between the materials. The angle of repose for all the selected crops seed increased with the increase in moisture content. Angle of repose for onion, carrot and tomato increased by 6.22%, 11.86% and 2.21% when the moisture content increased by 60.68%, 58.6% and 60.48% respectively, (Table 4.1). The coefficient of determination of carrot, onion and tomato obtained from the regression models were 0.976, 0.957 and 0.961 respectively (Table 4.2). Similiar trends were observed for millet (konak *et al.,* 2002); Amaranthus (Ilori *et al.,* 2016) and cowpea (Firouzi and Alizadeh, 2012).

Coefficient of friction

The coefficient of friction indicated the flowability of material, giving an idea about the interaction of the seed over the surface. The developed regression models showed significant effect of moisture content on coefficient of friction for all the vegetable seeds. The mean coefficient of friction increased for all the material surfaces with the increase in moisture content (Table 4.3).

Table 4.3. Variation of coefficient of friction at different moisture levels for different material surfaces

Moisture content(%wb)	Wood	Mild steel	Aluminium	Galvanized iron
Carrot				
8.15	0.50±0.01	0.45±0.03	0.40±0.01	0.47±0.03
12.01	0.57±0.04	0.54±0.02	0.53±0.01	0.54±0.01
16.37	0.65±0.02	0.57±0.01	0.61±0.02	0.58±0.02
20.73	0.66±0.01	0.61±0.01	0.63±0.01	0.60±0.01
Onion				
8.65	0.45±0.01	0.41±0.03	0.40±0.02	0.40±0.02
12.32	0.47±0.02	0.43±0.01	0.45±0.01	0.45±0.01
16.82	0.52±0.02	0.49±0.02	0.47±0.01	0.47±0.02
20.88	0.53±0.01	0.50±0.01	0.50±0.01	0.50±0.01
Tomato				
8.15	0.51±0.02	0.47±0.01	0.52±0.02	0.50±0.01
12.70	0.52±0.01	0.55±0.01	0.58±0.01	0.52±0.01
16.53	0.59±0.01	0.59±0.02	0.60±0.01	0.57±0.02
20.57	0.61±0.01	0.64±0.02	0.62±0.01	0.61±0.02

Values are mean±SE

Table 4.4. Regression model for coefficient of friction as a function of moisture content on different material surfaces

Material surface	Carrot			Onion			Tomato		
	Regression equation	R^2	P	Regression equation	R^2	P	Regression equation	R^2	P
Wood	0.012x+0.410	0.932	0.035	0.006x+0.394	0.953	0.024	0.009x+0.424	0.910	0.046
Mild steel	0.012x+0.370	0.934	0.034	0.007x+0.341	0.958	0.021	0.013x+0.370	0.979	0.010
Aluminium	0.018x+0.282	0.902	0.050	0.008x+0.334	0.972	0.014	0.007x+0.469	0.940	0.030
GI	0.010x+0.404	0.920	0.041	0.007x+0.343	0.951	0.025	0.009x+0.408	0.966	0.017

R^2= coeff. of determination, $P<0.05$= significant at 5% level of significance, $P<0.01$= significant at 1% level of significance

The coefficient of determination (R^2) for carrot on wood, mild steel, aluminium and galvanized iron were 0.932, 0.934, 0.902, 0.920 whereas for onion were 0.953, 0.958, 0.972, 0.951 and that of tomato were 0.910, 0.979, 0.940, 0.966 respectively (Table 4.4). Similar trends were observed in red pepper (Üçer,*et al.* 2010) , millet grain (Adebowale *et al.* ,2012) and pigeon pea (Shepherd and Bhardwaj, 1986).

4.2 Seed drying kinetics

Drying kinetics presents the drying behaviour of seeds with respect to moisture content and time. The effect of different drying temperature on selected vegetable seeds was evaluated. The initial moisture content of all the crop seeds was 20±1% wet basis. The three different selected seeds were dried till the safe moisture level of 8±1% wet basis. The drying behaviour of the selected three seeds are discussed below.

4.2.1 Effect of temperature on drying characteristics of different seeds

The variations of the moisture content versus drying time, drying rates versus drying time and moisture ratios versus drying time of onion [Fig. 4.1 (a), 4.2 (a), 4.3 (a)], carrot [Fig. 4.1 (b), 4.2 (b), 4.3 (b)] and tomato [Fig. 4.1 (c), 4.2 (c), 4.3 (c)] obtained at different temperature were plotted. It was observed that the moisture content decreased with drying time. A total of 75 min was less to dry the seeds when drying air temperature was kept at 40ºC compare to 35ºC. However, air temperature of 35ºC took 45min less than 30ºC for all the vegetable seeds to reach the same moisture content. Onion seeds took 315 min to reach 10.56 % d.b. at 30ºC whereas 195min to reach 9 % d.b. at 40ºC. Similarly, carrot and tomato seeds required 315min to reach 9.84 and 9.23 % d.b. at 30ºC whereas 195min to reach 8.53 and 8.59 % d.b.

at 40ºC, respectively. Moisture ratio decreased as the drying proceeded at all temperatures for all the vegetable seeds (Fig. 4.2). The relationship between moisture ratios with drying time was studied to find the best model of drying kinetics.

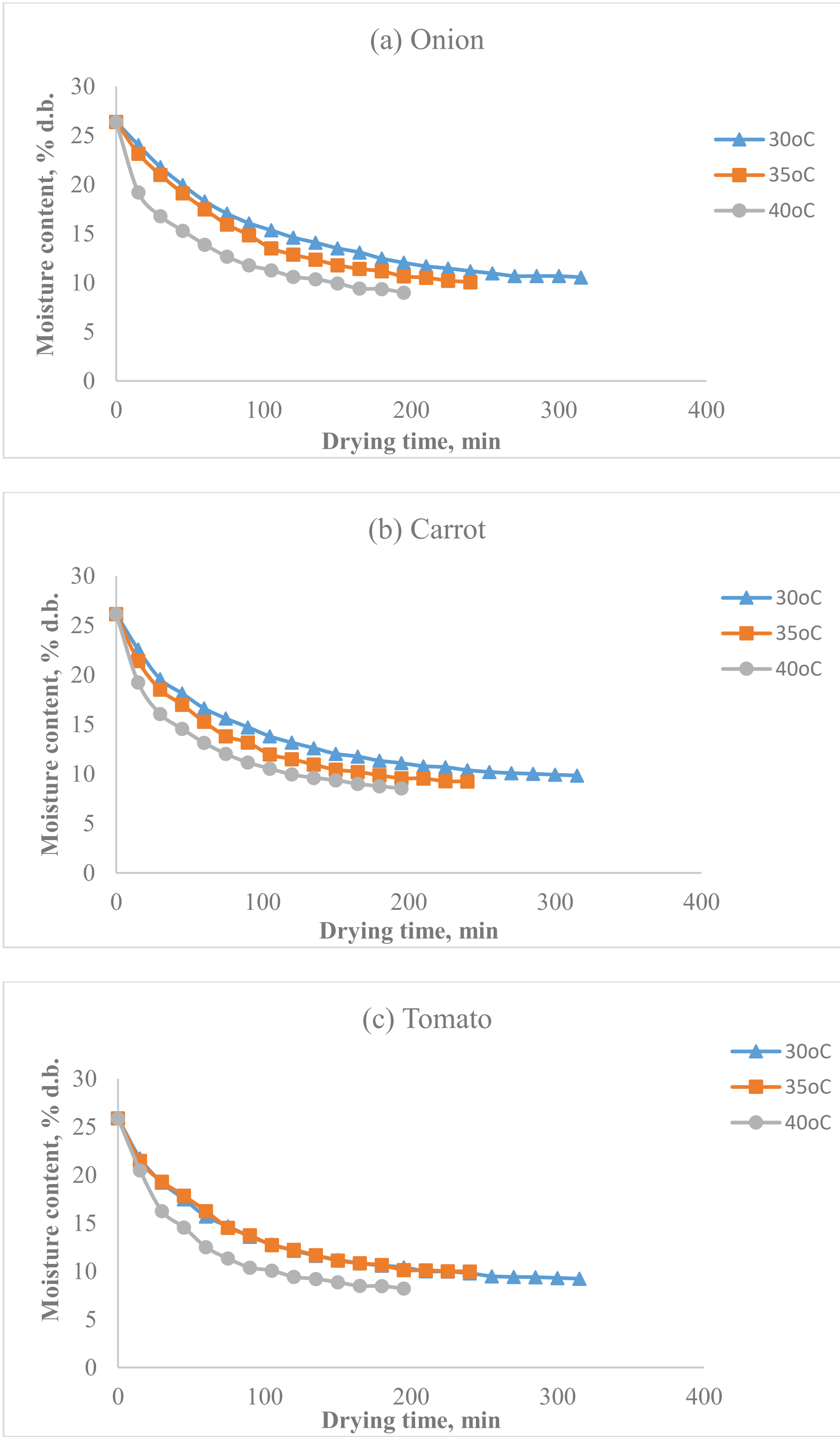


Fig. 4.1 Variation of moisture content with drying time at different drying air temperature (a) onion (b) carrot and (c) tomato.

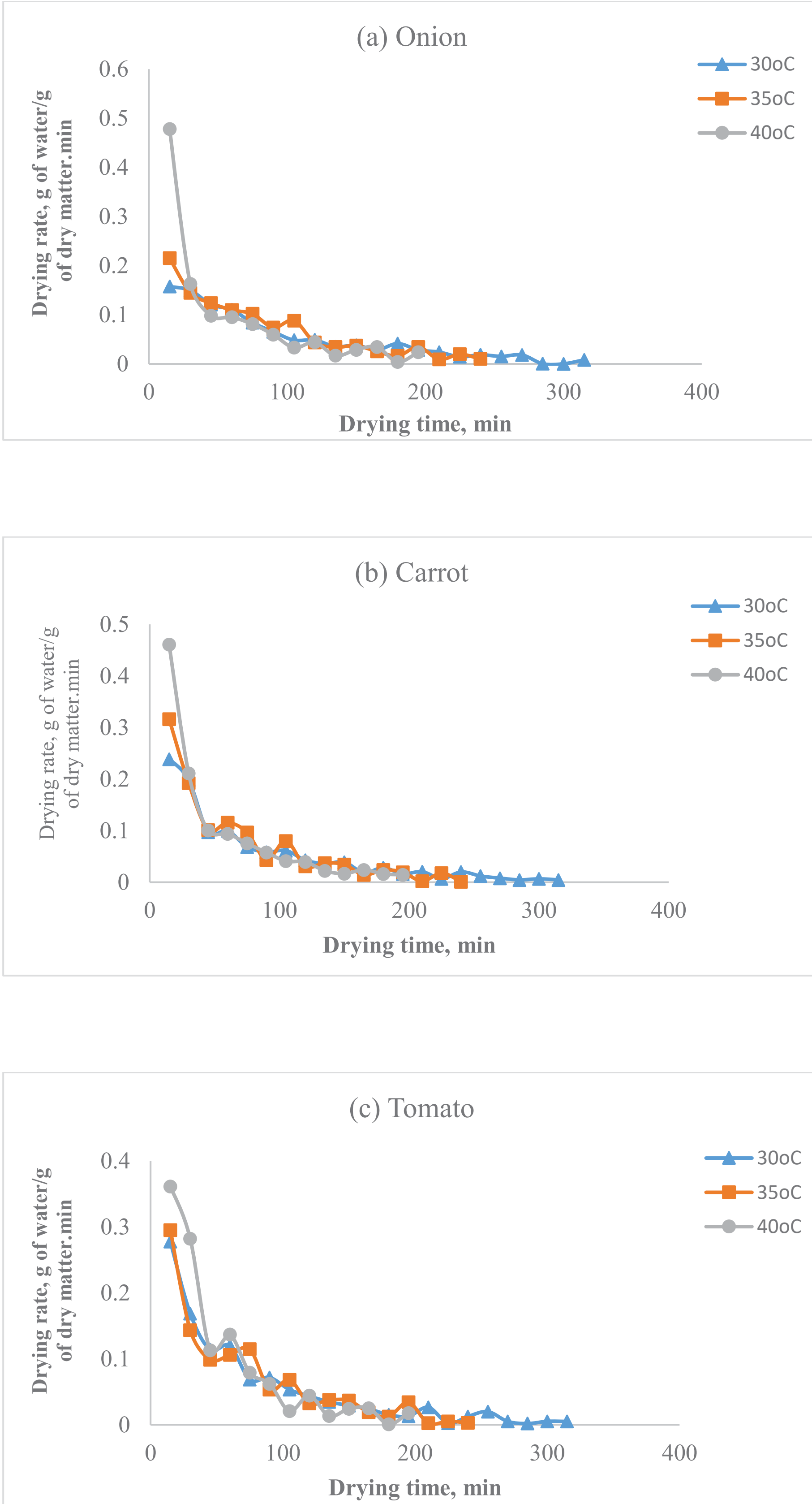


Fig. 4.2 Variation of drying rate with drying time at different drying air temperature (a) onion (b) carrot and (c) tomato.

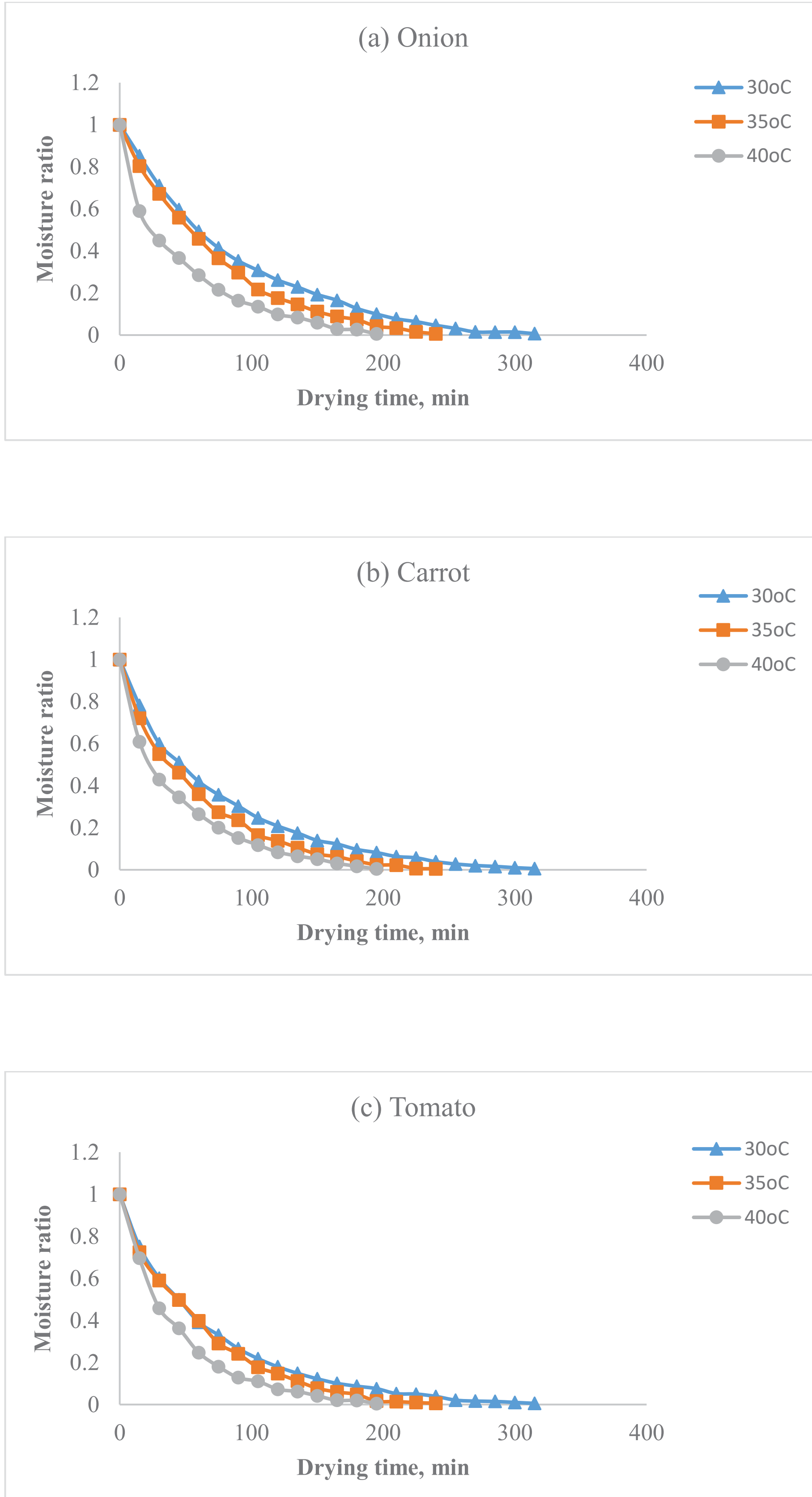


Fig. 4.3 Variation of moisture ratio with drying time at different drying air temperature (a) onion (b) carrot and (c) tomato.

4.2.2 Modelling of drying kinetics

Modelling of drying curves

The experimental data of moisture content measured at different points of time was converted into dimensionless ratio to compare various model. In general, the moisture ratio of selected vegetable seeds decreased at all the temperatures with time. Moisture ratio decreased at a higher rate in the beginning of the drying and become low as the moisture content decreased. Thus, the exponential decay of moisture content with time and absence of constant drying rate was observed. Similar observations were obtained by Gazor and Mohsenimanesh, 2010; Abano *et al.,* 2011 in canola and tomato slices, respectively.

The dimensionless moisture ratio against drying time for the vegetable seeds at different drying temperature were fitted to different drying kinetics models listed in Table 3.3.

The goodness of fit of the models were selected according to statistical parameters with highest R^2 value and lowest $\chi 2$, RMSE and SEE value. The highest R^2 and lowest value of χ^2 , SEE and RMSE indicated the goodness of fit of the model. Different model parameters along with the statistical parameters for onion, carrot and tomato, respectively were compared (Table 4.5, Table 4.6 and Table 4.7). All models had R^2 value greater than 0.9 except logarithmic model and Wang and Singh at 40ºC for onion and carrot. Page model was found to be the best model to describe the drying kinetics of onion at 40ºC with R^2 0.9951 whereas that of 30ºC and 35ºC was best fitted with two term exponential model with R^2 of 0.9979 and 0.9984, respectively, [Table 4.5, Annexure-I(A)].

Table 4.5. Drying kinetics model parameters for onion seeds

Drying temp. (°C)	Model Name	Parameter values				
		a	b	c	k	n
30, onion	Newton				0.011	
	Page				0.010	1.030
	Modified page				0.107	0.107
	Henderson and Pabis	1.0074			0.011	
	Logarithmic	0.7585		0.2415	139.41	
	Two term exponential	1.3838			0.012	
	Wang and Singh	-0.0079	0.00002			
35	Newton				0.014	
	Page				0.009	1.080
	Modified page				0.118	0.118
	Henderson and Pabis	1.0130			0.014	
	Logarithmic	0.7464		0.2536	112.39	
	Two term exponential	1.5366			0.016	
	Wang and Singh	-0.009	0.00003			
40	Newton				0.022	
	Page				0.060	0.758
	Modified page				0.151	0.148
	Henderson and Pabis	0.9279			0.020	
	Logarithmic	0.8073		0.1927	113.2	
	Two term exponential	0.1962			0.094	
	Wang and Singh	-0.0138	0.00005			

Similarly, Page model described the best fit for drying air temperature of 35°C and 40°C with R^2 of 0.9973 and 0.9975 respectively for carrot. However, Two term exponential describe the best fit for 30°C having R^2 of 0.9988 with minimum value of ME (0.0095), RMSE (0.090) and $\chi2$ (8.9E-05), Table 4.6, Annexure-I(B).

Table 4.6. Drying kinetics model parameters for carrot seeds

Drying temp. (°C)	Model Name	Parameter values				
		A	b	c	k	n
30, carrot	Newton				0.0138	
	Page				0.0218	0.8993
	Modified page				-0.1181	-0.116
	Henderson and Pabis	0.962			0.0133	
	Logarithmic	0.796		0.2040	672.95	
	Two term exponential	0.110			0.1114	
	Wang and Singh	-0.008	0.00002			
35	Newton				0.0175	
	Page				0.0242	0.9245
	Modified page				-0.1321	-0.132
	Henderson and Pabis	0.9706			0.0170	
	Logarithmic	0.7969		0.2031	4075.16	
	Two term exponential	0.5649			0.0229	
	Wang and Singh	-0.011	0.00003			
40	Newton				0.0237	
	Page				0.0562	0.7853
	Modified page				0.1489	0.1591
	Henderson and Pabis	0.9424			0.0222	
	Logarithmic	0.8174		0.1826	10173.3	
	Two term exponential	0.2080			0.0925	
	Wang and Singh	-0.014	0.00005			

Also, the model that described the best for tomato seeds is Page model in all the selected temperature range (Table 4.7). The coefficient of determination (R^2) at 30, 35 and 40°C were 0.9993, 09958 and 0.9986, respectively, Annexure-I (C). Hence, it can be noted that drying kinetics of selected vegetable seeds for different temperature can be best described by either Page model or Two Term Exponential model. However, the least goodness of fit was observed in Logarithmic model. Similar patterns were observed by Cantu-Lozano *et al.*, 2013 in grape seeds and Sogi *et al.*, 2003 for tomato seeds. However, logarithmic model was found to be the best for canola seed dried in fluidized bed dryer (Gazor and Mohsenimanesh, 2010).

Table 4.7. Drying kinetics model parameters for tomato seeds

Drying temp. (°C)	Model Name	Parameter values				
		a	b	c	k	n
30, tomato	Newton				0.0149	
	Page				0.0237	0.8959
	Modified page				-0.1217	-0.1225
	Henderson and Pabis	0.9628			0.0143	
	Logarithmic	0.8105		0.1895	2172.76	
	Two term exponential	0.4025			0.0272	
	Wang and Singh	-0.009	0.00002			
35	Newton				0.0165	
	Page				0.0185	0.9737
	Modified page				-0.1301	-0.1270
	Henderson and Pabis	0.9794			0.0162	
	Logarithmic	0.7871		0.2129	4052.78	
	Two term exponential	1.1860			0.0170	
	Wang and Singh	-0.010	0.00003			
40	Newton				0.0232	
	Page				0.0312	0.9264
	Modified page				-0.1509	-0.1540
	Henderson and Pabis	0.9855			0.0229	
	Logarithmic	0.8154		0.1846	5234.3	
	Two term exponential	0.4971			0.0341	
	Wang and Singh	-0.014	0.00005			

4.2.3 Optimization of temperature and moisture content with respect to seed properties

Central composite face centered design was employed to study the effect of drying temperature and moisture content on seed quality. Outline of the experimental design were made with their respective levels for onion, carrot and tomato (Annexure-

II). Independent variables were temperature (30, 35, 40ºC) and moisture content (12, 14, 16 % w.b.). Drying temperature and initial moisture content were optimized based on the seed response parameters, namely, germination percentage (GP), vigor (vigor index I, and vigor index II), infected seed (IS) and electrical conductivity (EC). Number of infected seeds in the given seed lots provided the status of seed health. Electrical conductivity test was performed to predict the seed coat intactness. The responses obtained were optimized using Design Experts program (version 10.0.0) of the STAT-EASE software. The analysis of variance for the fit of experimental data to response surface model for onion, carrot and tomato, respectively were studied.

The seed quality parameters of onion such as germination percentage [Plate 4.1 (a), (b) and (c)], electrical conductivity, number of infected seeds [Plate 4.1 (d), (e) and (f)], Vigor index-I and vigor index-II with respect to temperature and moisture content are listed in Annexure-II (A). The optimized temperature and moisture content was analyzed considering the best seed quality i.e. maximum germination percentage, vigor index-I and vigor index-II and minimum infected seeds and electrical conductivity. The analysis of variance (ANOVA) for onion, Annexure-III (A), revealed that coefficient of determination (R^2) for all the seed properties were more than 0.96 except for infected seeds which has R^2 value of 0.6944. Coefficient of variation (CV) was more than 10 for infected seeds whereas it was less for other responses indicating less reasonable accuracy of the experiments except for the infected seeds. However, the model correlated well with the measured data as indicated by the non-significant lack-of-fit ($p<0.05$). All the response parameters showed high adequate precision (>4). Thus, the generated model approximate the response surfaces. Therefore, it can be used for prediction of any values of the parameters within the experimental range.

Equation for each of the response variable could be derived using the predicted values i.e. regression coefficient of each response variable. It can also be interpreted that quality parameters of onion seed i.e. electrical conductivity, germination percentage, infected seed and vigor index II were significantly increased ($p<0.01$) with the increase in temperature and at higher moisture content (Table 4.8; Fig. 4.4). However, vigor index-I decreased with the increased in moisture content.

(a) Germinated tomato seeds

(b) Germinated onion seeds

(c) Germinated carrot seeds

(d) Seed health testing for tomato seeds

(e) Seed health testing for carrot seeds

(f) Seed health testing for onion seeds

Plate 4.1. Germination and infected seed test.

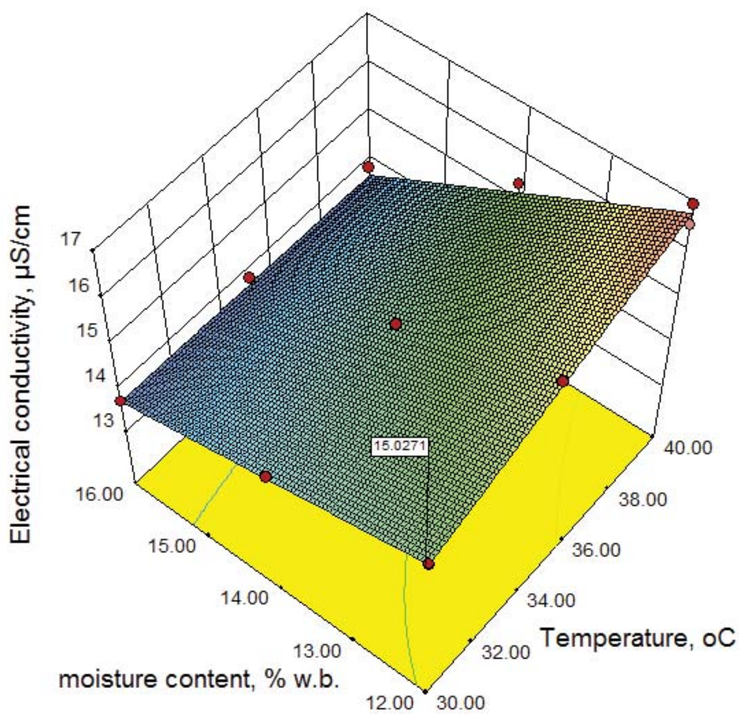
Table 4.8. Regression Coefficients for fitted Models for onion seeds

Onion	Responses				
Parameters,	EC, µS/cm	GP, %	IS	VI-I	VI-II
Constant	-2.37012**	9.85050**	-1.100**	101.81920**	-148.833**
A. Temperature	0.71205**	2.36805**	1.2445x10-5**	-1.81550*	34.9178**
B. Moisture	1.01784**	6.29225**	0.25000**	-5.57193**	90.8624**
AB	-0.044905**	-0.22175**	-8.439E-017**	0.13212**	-3.09741**

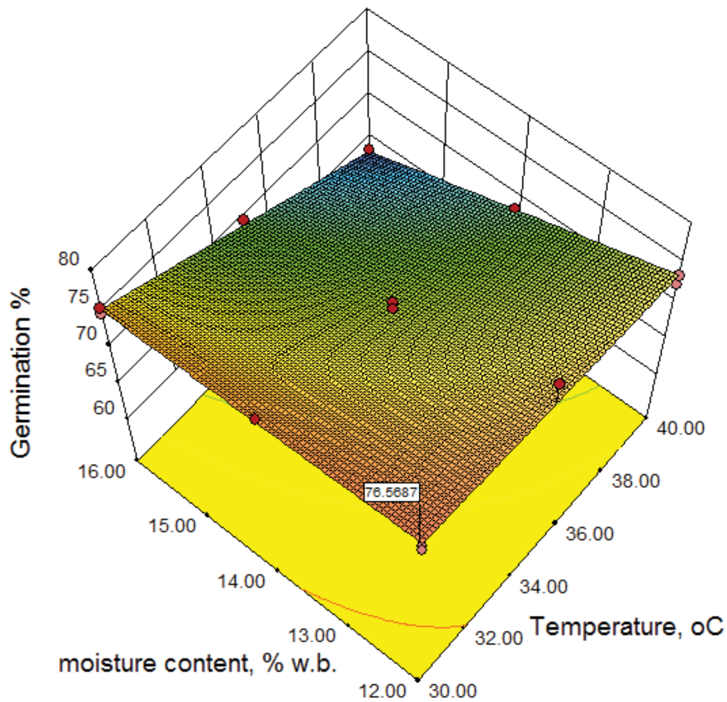
*Significant at p<0.05 and **Significant at p<0.01.

The best responses of onion seed quality was observed at 30ºC and 12.04% w.b. moisture content with desirability of 0.864.

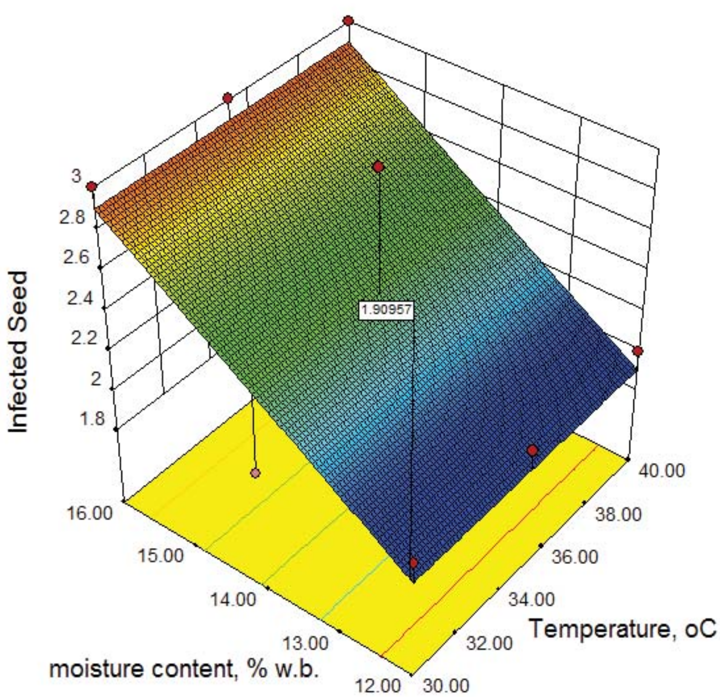
Onion



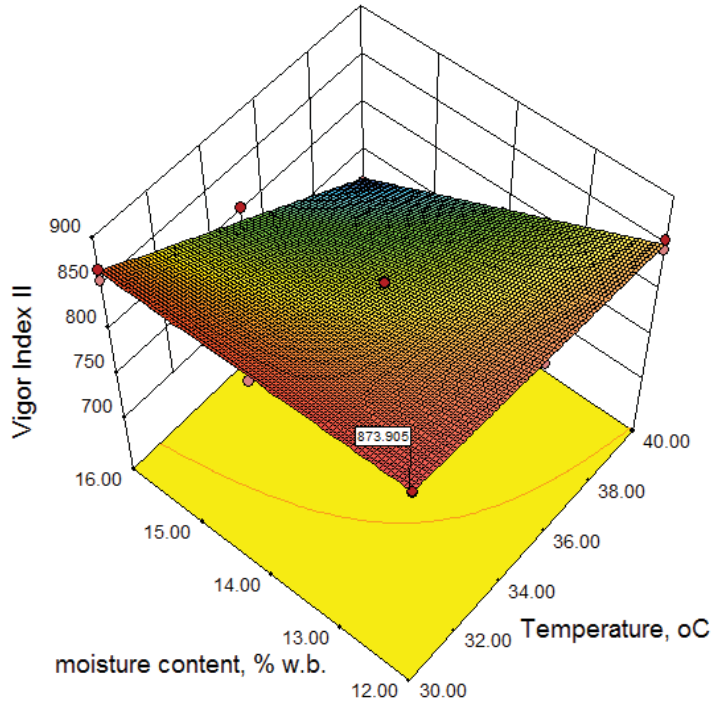
(a) Effect of moisture content and temperature on electrical conductivity of onion seed



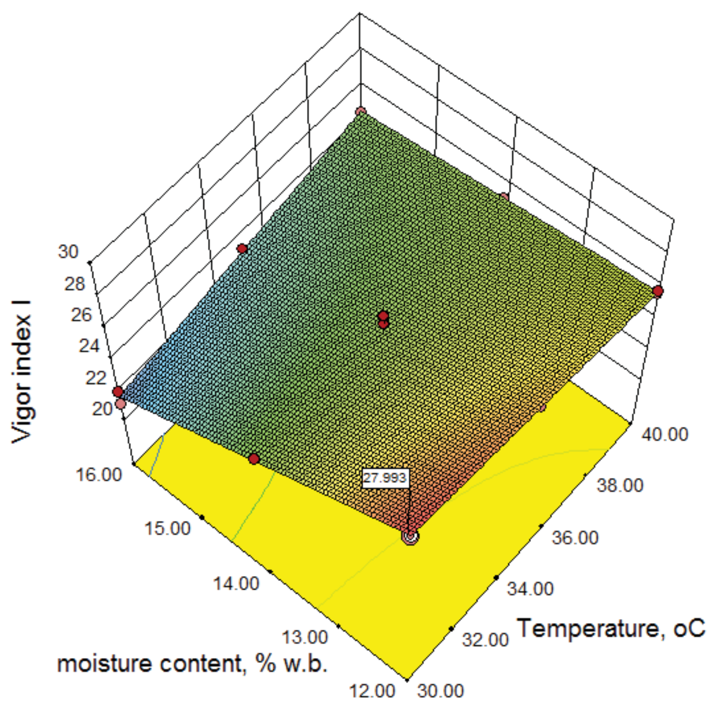
(b) Effect of moisture content and temperature on germination of onion seed



(c) Effect of moisture content and temperature on number of infected seeds for onion



(d) Effect of moisture content and temperature on vigor index-II of onion seed



(e) Effect of moisture content and temperature on vigor index-I of onion seed

Fig.4.4 Variation of responses with respect to temperature and moisture content of onion seeds

Outline of the experimental design for carrot showed the number of runs with respective responses of seed quality parameters (Annexure-II, B). The electrical conductivity, germination percentage, infected seeds, vigor index-I, vigor index-II ranged from 40.857 to 46.765µS/cm, 56.72 to 67.45%, 4 to 7, 559.48 to 662.06 and 10.62 to 12.33, respectively within the range of temperature studied.

The ANOVA (Annexure-III, B) for carrot indicated that coefficient of determination for all the responses were more than 0.9 except for infected seeds which was 0.82. It also indicated that adequate precision being more than 4 for all the response parameters, the model was highly desirable. Coefficient of variation was less than 10 for all the response parameters. But, non-significant lack of fit ($p<0.05$) revealed that the measured data correlated well with the model. Thus, the generated model can be used to predict data for the response parameters within the experimental range.

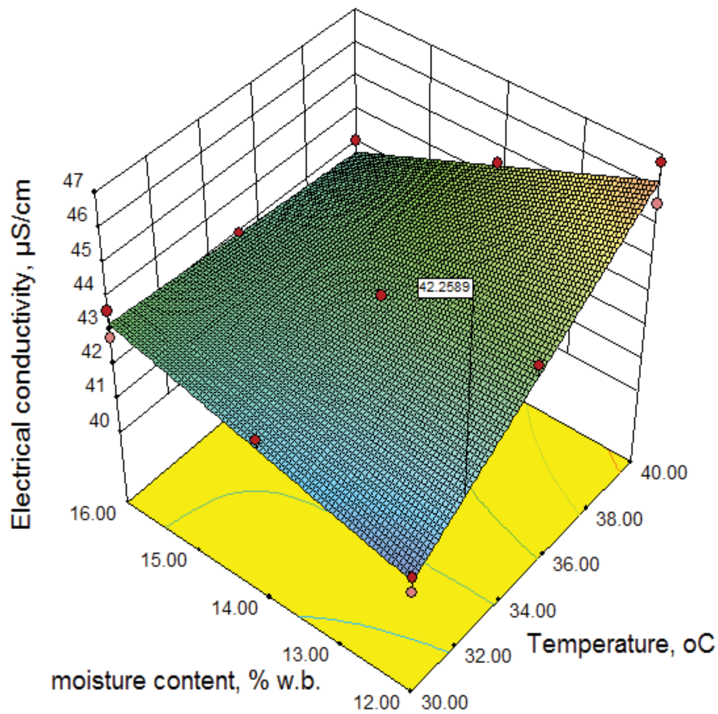
Table 4.9. Regression coefficient for fitted models of carrot seeds

Carrot	EC, µS/cm	GP, %	IS	VI-I	VI-II
Constant	-30.415**	211.64**	42.12**	540.21**	42.93**
A. Temperature	2.1787**	-4.22**	-1.15**	7.69**	-0.824**
B. Moisture	4.70701**	-9.86	-2.33**	15.21**	-2.3**
AB	-0.1394**	0.276**	0.075**	-0.82**	0.60**

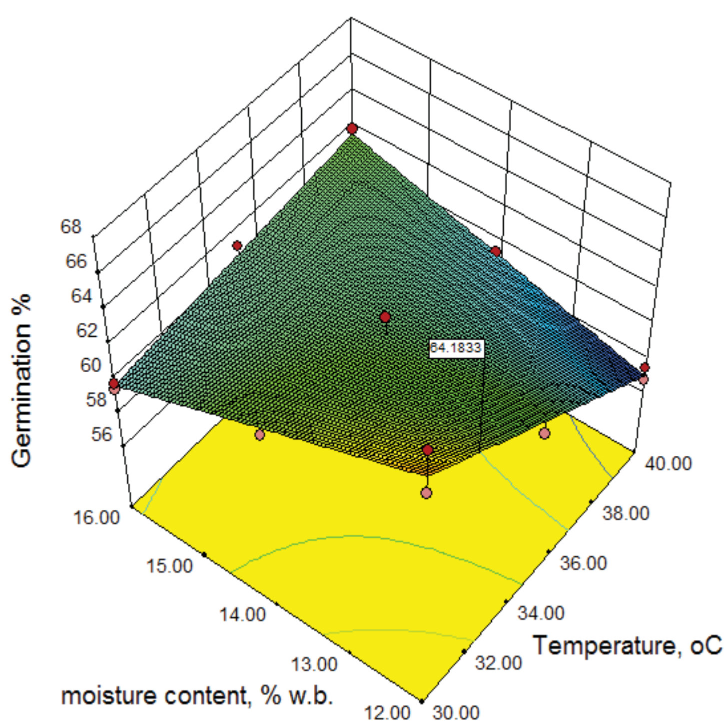
*Significant at $p<0.05$ and **Significant at $p<0.01$.

The regression coefficient can be used to derive the equation of each response variables (Table 4.9). It was observed that electrical conductivity and vigor Index-I of carrot seeds significantly increased with the increased in temperature and at higher moisture content ($p<0.01$), (Fig. 4.5). However, germination percentage and number of infected seeds and vigor index-II significantly decreased at higher temperature and moisture content (Table 4.9). It was observed that all the responses were significantly affected by temperature and moisture at two level factorial interaction and was found to be significant ($P<0.01$).

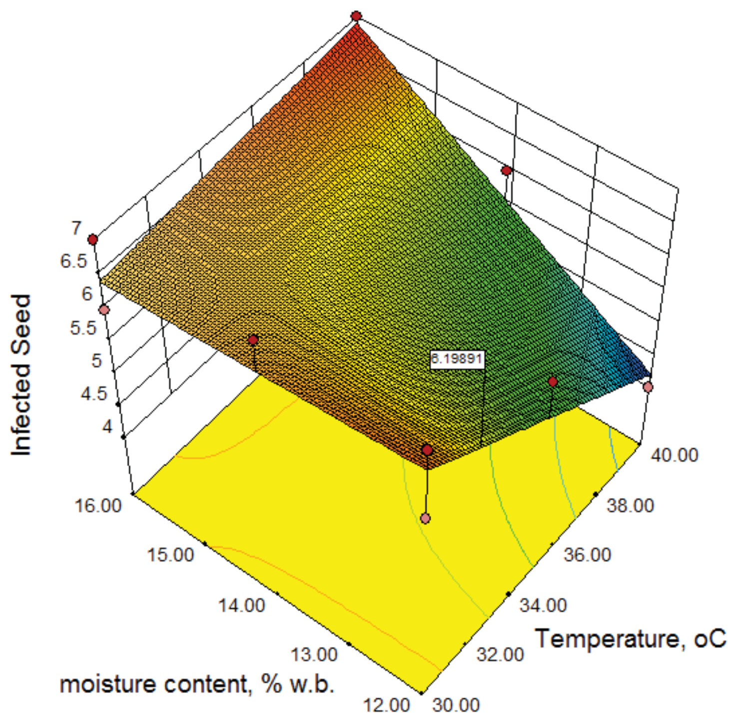
Carrot



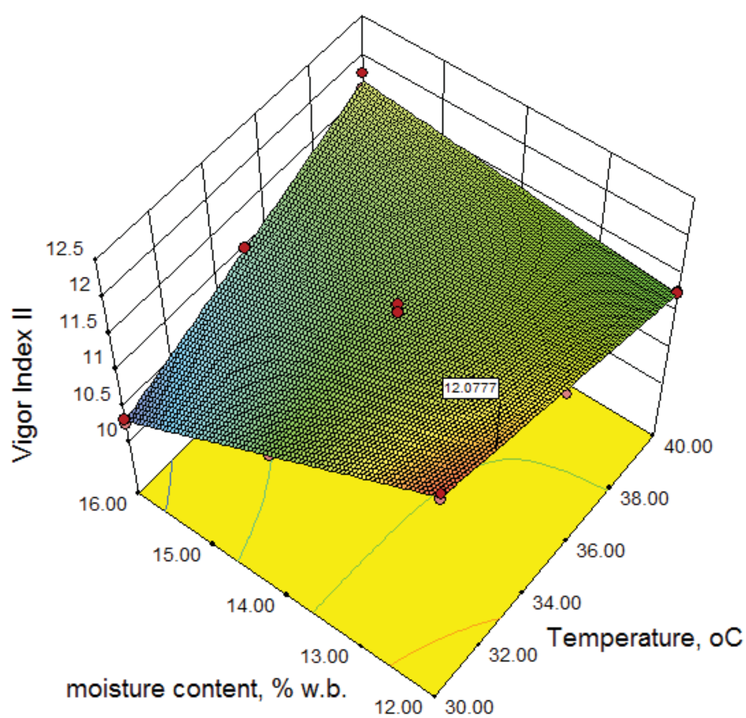
(a) Effect of moisture content and temperature on electrical conductivity of carrot seed



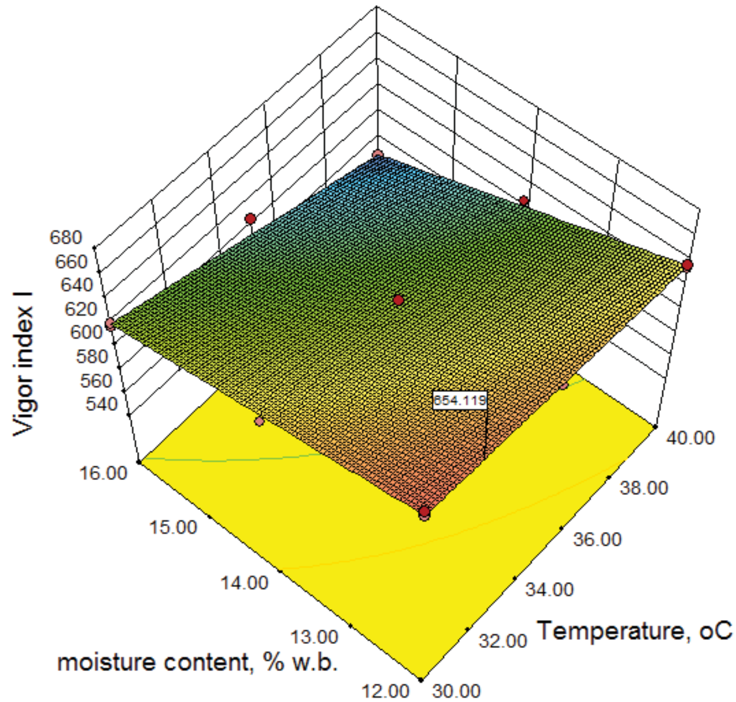
(b) Effect of moisture content and temperature on germination of carrot seed



(c) Effect of moisture content and temperature on number of infected seeds of carrot seed



(d) Effect of moisture content and temperature on vigor index-II of carrot seed



(e)Effect of moisture content and temperature on vigor index-I of carrot seed

Fig.4.5 Variation of responses with respect to temperature and moisture content of carrot seeds

From the analysis of all the responses, it can be concluded that the optimized temperature and moisture content for the best response for carrot was at 32.07ºC of drying and 12% w.b. moisture content with desirability of 0.649.

The experimental design outline for tomato was formulated with number of experimental runs and responses, Annexure-II (C). The maximum value of electrical conductivity, germination percentage, number of infected seeds, vigor index-I and vigor index-II were 10.97µS/cm, 48.98%, 10,686.76, 18.32 whereas the minimum value were 9.69 µS/cm, 39%, 4, 547.3 and 14.19 respectively, within the experimental range.

The analysis of variance (ANOVA) for tomato seeds showed that the coefficient of determination (R^2) for all the seed properties were more than 0.9 indicating the high acceptability of the model of each response, (Annexure-III, C). Coefficient of variation (CV) was less than 10 for all the response parameters. High adequate precision was observed for all the responses. Also, non-significant lack-of-fit ($p<0.05$), indicated the good correlation between the model and the measured data.

Therefore, the developed model can be used for prediction of response parameters using the model within the experimental range.

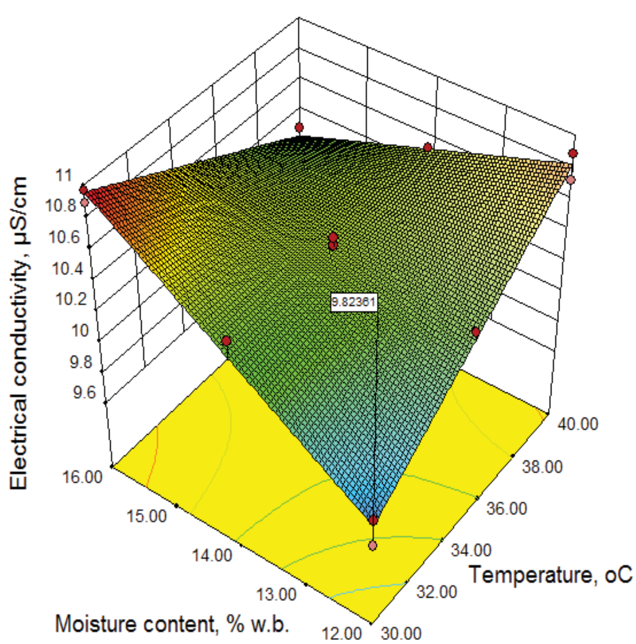
Table 4.10. Regression coefficient for fitted models of tomato seeds

Tomato	EC, µS/cm	GP, %	IS	VI-I	VI-II
Constant	-12.16**	74.994**	-5.84**	2589.29**	57.86**
A. Temperature	0.62**	-0.35**	0.165**	-52.73**	-0.914**
B. Moisture	1.58**	-1.28**	0.063**	-128.39**	-2.75**
AB	-0.043**	-2.27×10^{-3}**	0.013**	3.36**	0.058**

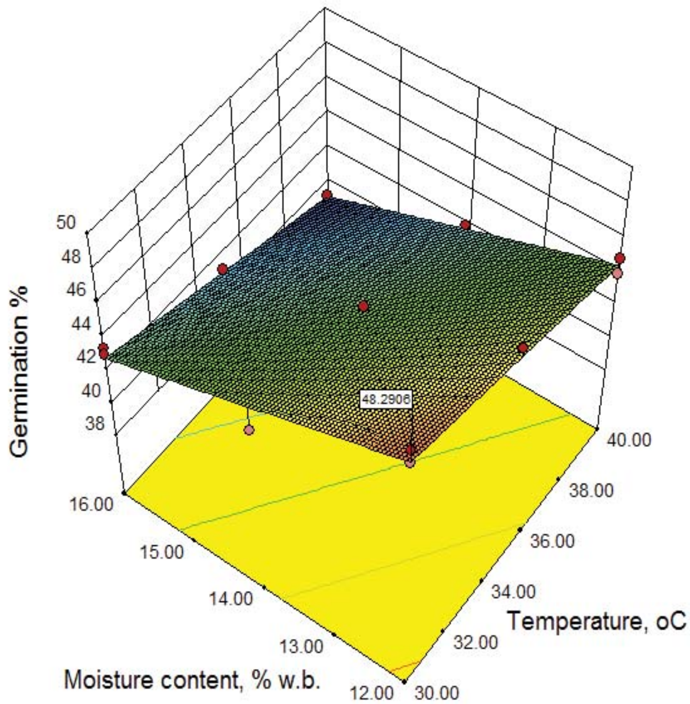
*Significant at p<0.05 and **Significant at p<0.01.

Model equation can be derived using regression coefficient of each responses (Table 4.10). Germination percentage, vigor index-I and vigor index-II of tomato decreased significantly with increased in moisture content (p<0.01). Also, high drying air temperature resulted in decreased of germination percentage, vigor index-I and II. However, electrical conductivity and number of infected seeds increased at higher temperature (Table 4.10, Fig. 4.6). All the responses were significantly affected by temperature and moisture content at two level factorial interaction. The interaction of temperature and moisture content has also significant effect on the response parameters.

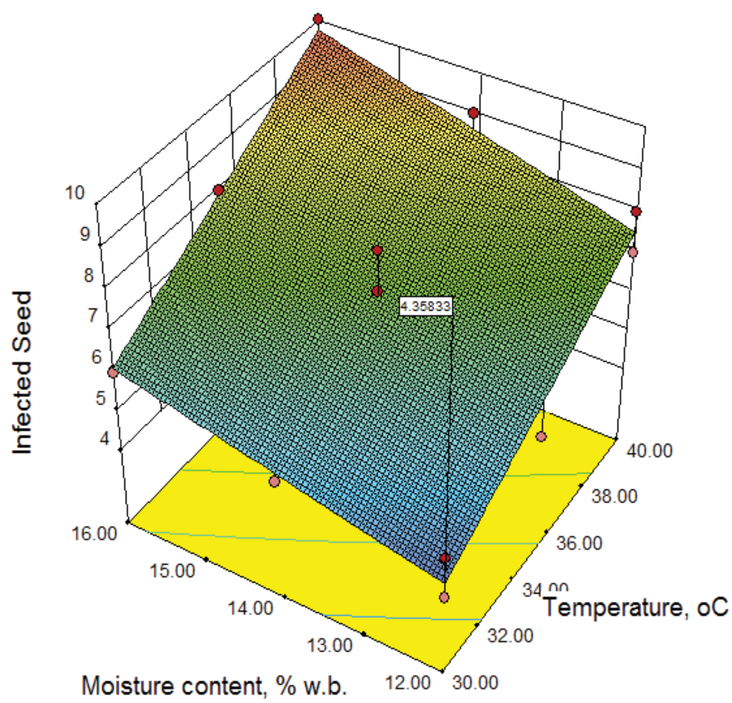
Tomato



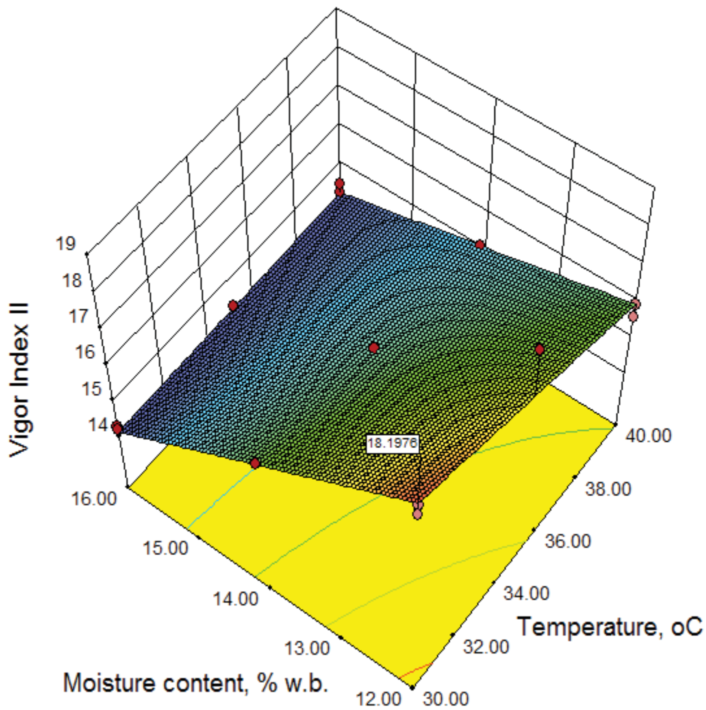
(a) Effect of moisture content and temperature on electrical conductivity of tomato seeds



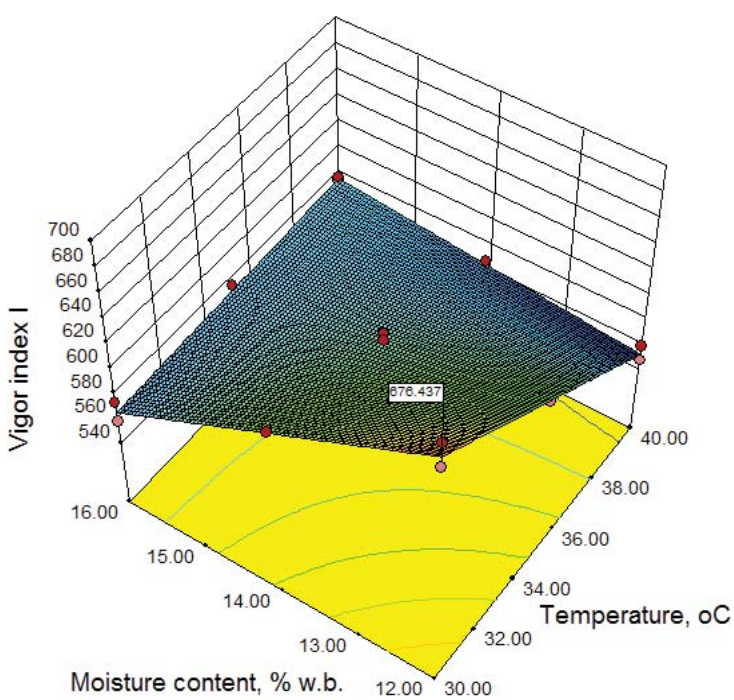
(d) Effect of moisture content and temperature on germination of tomato seeds



(c) Effect of moisture content and temperature on number of infected of tomato seeds



(e) Effect of moisture content and temperature on number of vigor index-II of tomato seeds



(f) Effect of moisture content and temperature on vigor index-I of tomato seed

Fig 4.6 Variation of responses with respect to temperature and moisture content of tomato seeds

Drying air temperature of 30ºC and 12% w.b moisture content was found to be the optimized value for tomato considering the best seed quality responses with desirability of 0.933.

4.3 Design values for development of solar vegetable seed dryer

The designed vegetable solar seed dryer with capacity of 3 kg seed consisted of different units, namely, air distribution unit [Plate 4.2 (a)], water heating unit [Plate 4.2 (b), (c) and (d)], heat transfer unit [Plate 4.2 (e)] and power supply unit [Plate 4.2 (f), (g) and (h)]. The design parameters and values are listed in Table 4.11.

Table 4.11. Designed values for the developed dryer

Sl. No.	Parameters	Values
1.	Capacity of the dryer	3kg
2.	Mass of moisture to be removed	0.4kg
3.	Energy required to remove the moisture	770KJ
4.	Flow rate of air	$0.04m^3/s$
5.	Capacity of heat exchanger	0.5TR
6.	Pump capacity	0.25hp
7.	Fan rating	920rpm, 15inch
8.	Solar water heater	200L/day
9.	Hot water storage tank	250L
10.	Solar photovoltaic panel	400W
11.	Solar battery	12V
12	Inverter	230V AC output, 12V DC supply
13	Temperature controller	16A SSR relay, 220V AC
14	Inside chamber dimension	(60x30x76)cm
14	Outside chamber dimension	(70x50x82)cm
15	Insulation thickness	4cm
16	Air vent or air passage	5cm
17	No. of trays	7
18	Rectangular hole for air passage at both side of bottom	(15x5)cm
19	Dimensions of the air duct for both side	(15x5)cm
20	Dimensions of hopper	(40x35)cm, larger opening (15x12)cm, smaller opening
21	Total number of holes	70

The power required to run the dryer was solely derived from solar energy, utilizing both thermal and electrical power. The thermal energy was stored in the form of sensible heat in water and transfer it to the dryer through heat exchanger (0.5 TR). Hot air was blown to the drying chamber through heat exchanger by a fan. The power required to operate the fan, pump (0.25 hp) for hot water and temperature controller were supplied through solar photovoltaic panel. The design values were evaluated based on the capacity and the amount of energy required to remove the moisture content to bring to the safe level. Plate 4.3 shows the set-up of the dryer with different units. The designed parameters were used to develop vegetable seed dryer.

4.3.1 Efficiency of the developed dryer

The dryer efficiency is defined as the ratio of amount of heat utilized by the dryer to the amount of heat supplied to the air. The efficiency of the dryer was calculated using the following equation.

$$\eta_{dryer} = \frac{m_p c_p \Delta T_p + m_w h_{fg}}{Q_a}$$

Sensible heat of the product = $m_p c_p \Delta T_p$ =3 x 2.341 x (33-26) =49.161kJ= 50kJ (approx.)

Latent heat = $m_w h_{fg}$ = 0.4 x 1800 = 720kJ

Therefore, amount of heat energy to remove the moisture, Q= (720+50) kJ =770kJ

Considering 7 hours of drying time, Q= 0.031kW

Q_a= $m_a c_{pa} \Delta T_a$ = 0.049x 1.005x 1 [ma = mass flow rate of air=0.04m^3/sx1.225kg/m^3]

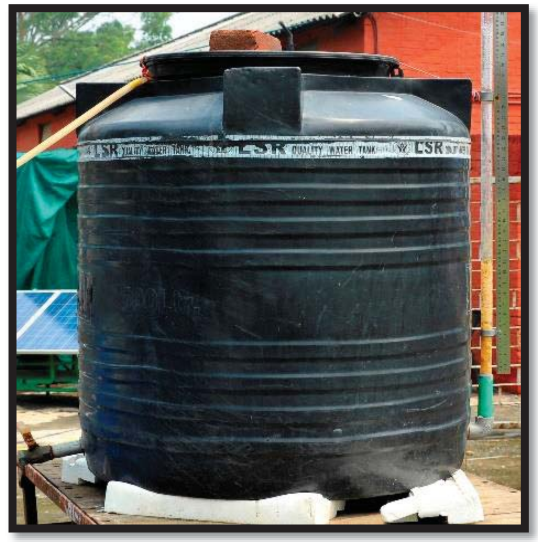
=0.049kW=0.05kW (approx.)

Hence, efficiency of the dryer, η_{dryer}= 0.031/0.05 =62%

4.3.2 Performance evaluation of the dryer

The performance of the dryer was evaluated at three different loads of 1 kg, 2 kg and 3 kg. The drying kinetics was studied at each load and the seed quality parameters were evaluated. Different drying curves i.e. (a) moisture content vs drying time (b) drying rate vs drying time (c) moisture ratio vs drying time were plotted for all the selected vegetable seeds at three different loads. Three models namely, Page, Henderson and Pabis and Two term exponential were selected based on the best model from the preliminary drying experiment on laboratory dryer. The model constants and

(a) Fan with air duct



(b) Water supply tank

(c) Solar water heater

(d) Hot water storage tank

(e) Motor

(f) Temperature controller

(g) Inverter, battery and MPPT

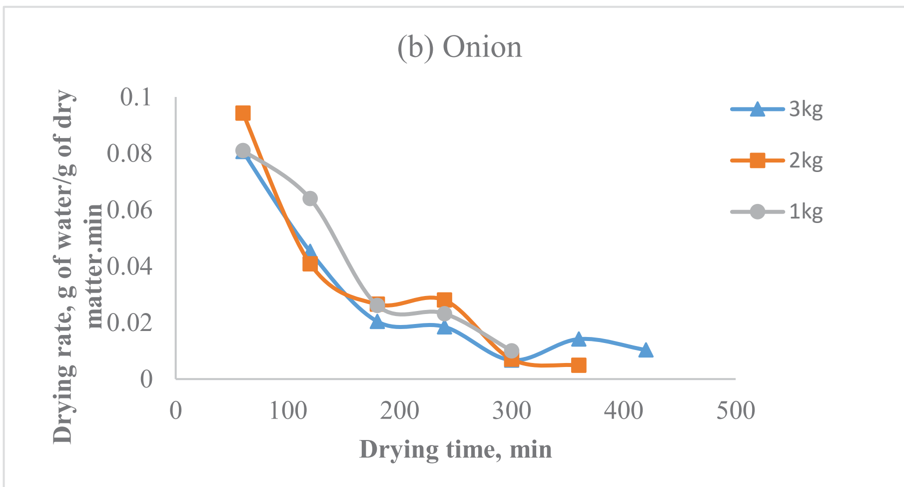
(h) Solar panel

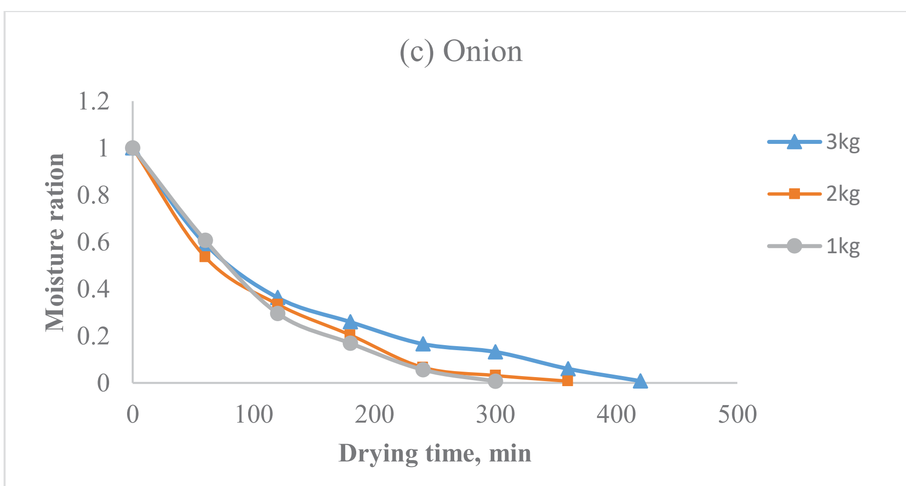
Plate 4.2. Different units of the developed dryer

Plate 4.3. Set-up of the developed dryer

statistical parameters were determined. Equation can be derived using the model constant of the particular load. The equation will give moisture ratio at best fit within the experimental time studied. Thus the drying behavior of the seed can be determined.

The onion seeds were dried in the developed dryer for performance evaluation. Experiment on onion seed drying gave good performance. The moisture content reduced as the drying time increased. An initial moisture content of 17.5% w.b. was reduced to 8.63% w.b., 8.36 % w.b., and 8.21% w.b. for 3kg, 2kg and 1kg load in 420 min, 360 min and 300min, respectively [Fig. 4.7(a)].





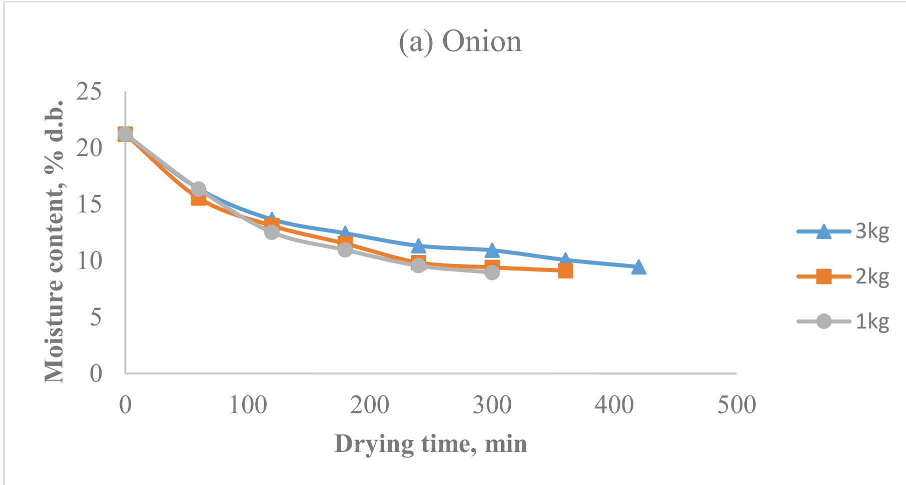


Fig. 4.7 Variation of (a) moisture content vs drying time (b) drying rate vs drying time (c) moisture ratio vs drying time at different drying air temperature for onion seeds.

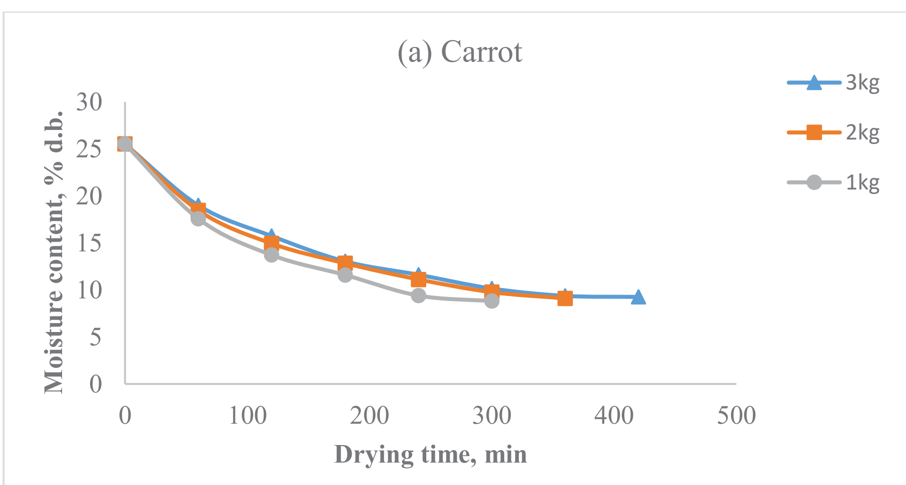
Drying kinetics revealed that higher load required more drying time to reduce the same amount of moisture content. Drying rate for all the load condition reduced with drying time. The drying rate was increased at the beginning of drying and reduced as the drying proceed and thus, it followed falling rate of drying and absence of constant rate of drying [Fig. 4.7(b)].

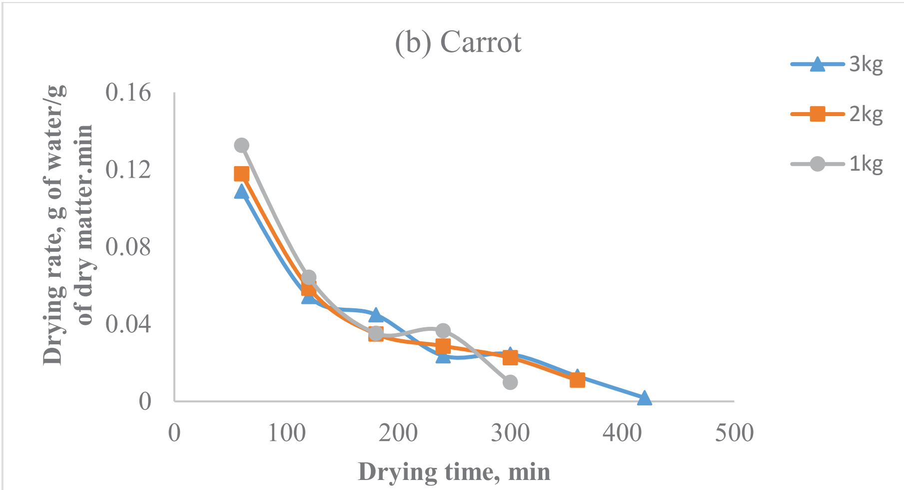
The moisture ratio also reduced exponentially with drying time [Fig. 4.7 (c)]. The moisture ratio values were 0.008, 0.007 and 0.007 at 3kg, 2kg and 1kg load at the end of drying. For modelling the drying kinetics of onion seeds, the moisture obtained with time was converted into moisture ratio and compare the selected drying models. The model parameters for onion are presented in Table 4.12. Considering all the statistical parameters i.e. coefficient of determination (R^2), Standard error (SE), Root mean square error (RMSE) and Chi-square ($\chi 2$), it was observed that the Two Term exponential model fit the best for all the experimental data. Also, Page and Henderson and Pabis model also have $R^2 > 0.99$ at all load. The R^2 values for 3kg, 2kg and 1kg for Two Term Exponential model were 0.9966, 0.9950 and 0.9982 respectively, (Table 4.17).

Table 4.12. Evaluated model parameters for onion seeds for performance evaluation

Model Name, onion	Parameter values			R^2	SEE	RMSE	χ2
	a	k	n				
3kg							
Page		0.0127	0.9066	0.9963	0.0028	0.0217	0.0147
Henderson and Pabis		0.0078	0.9850	0.9946	0.0041	0.0263	0.0152
Two term exponential	0.1012	0.0707		0.9966	0.0026	0.0209	0.0004
2kg							
Page		0.0092	1.0130	0.9950	0.0039	0.0278	0.0011
Henderson and Pabis		0.0098	0.9977	0.9949	0.0039	0.0279	0.0008
Two term exponential	0.0219	0.4379		0.9950	0.0038	0.0277	0.0008
1kg							
Page		0.0033	1.2300	0.9984	0.0012	0.0173	0.1723
Henderson and Pabis		0.0101	1.0190	0.9919	0.0059	0.0385	0.0016
Two term exponential	1.7860	0.0136		0.9982	0.0013	0.0181	0.0003

Similarly, the drying behaviour of the carrot seeds was evaluated from developed dryer for performance. The moisture content of carrot seeds reduced from 20.33 % w.b to 8.47 % w.b. for 3kg load at total drying time of 420min whereas that of 2kg and 1kg load, moisture content reduced to 8.34% w.b and 8.39% w.b., within 360min and 300min, respectively [Fig. 4.8(a)]. It showed that less time of drying for less load compared to higher load. Drying rate also reduced with drying time. However, the change in drying rate was almost same for all the load [Fig. 4.8(b)]. The drying rate was higher at the beginning of drying and reduced with drying time indicating absence of constant rate of drying.





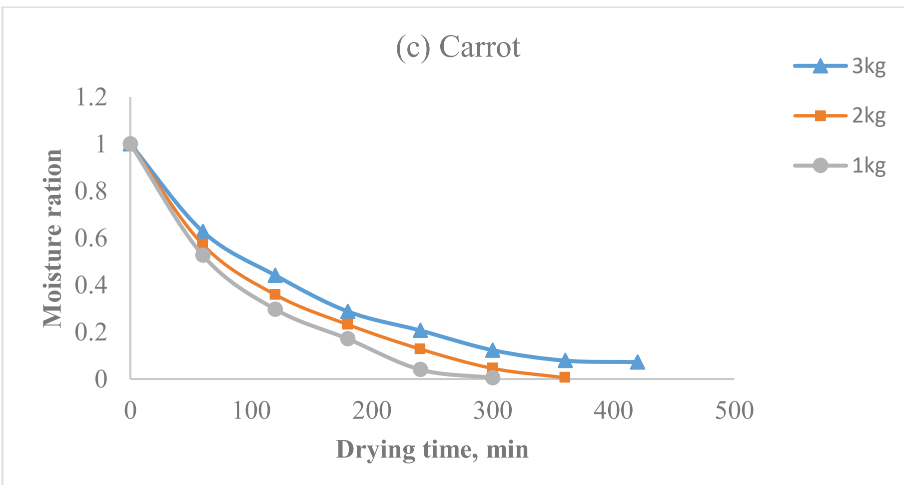


Fig. 4.8 Variation of (a) moisture content vs drying time (b) drying rate vs drying time (c) moisture ratio vs drying time at different drying air temperature for carrot seeds.

Moisture ratio of carrot seeds decreased with drying time [Fig. 4.8 (c)]. Moisture ratio for carrot seeds was calculated for modelling of drying kinetics and to find best model out of three selected models. The model parameters for carrot with respective statistical parameters for the selected model are listed in Table 4.13.

Table 4.13. Evaluated model parameters for carrot seeds for performance evaluation

Model Name, carrot	Parameter values			R^2	SEE	RMSE	χ2
	a	k	n				
3kg							
Page		0.0098	0.9332	0.9988	0.0009	0.0122	0.0095
Henderson and Pabis		0.0068	0.9870	0.9979	0.0015	0.0159	0.0003
Two term exponential	0.0669	0.0967		0.9991	0.0007	0.0105	0.0001
2kg							
Page		0.0085	1.0080	0.9957	0.0032	0.0253	0.0008
Henderson and Pabis		0.0088	0.9974	0.9957	0.0032	0.0253	0.0006
Two term exponential	1.3120	0.0095		0.9958	0.0031	0.0249	0.0006
1kg							
Page		0.0080	1.059	0.9955	0.0032	0.0283	0.0009
Henderson and Pabis		0.01066	1.003	0.9949	0.0004	0.0298	0.0009
Two term exponential	0.0064	1.658		0.9949	0.0036	0.0300	0.0009

Three drying kinetics models were compared for three different loads. For all the load tested, it was observed that two term exponential model gave the best fit for all the experimental data for carrot. The R^2 value for two term exponential was highest than Page and Henderson and Pabis model. Also, SSE, RMSE and χ2 of Two Term Exponential were comparatively less than other models.

The performance of the developed dryer was also evaluated using tomato seeds. The drying characteristics of the tomato seeds was studied and drying curves were plotted [Fig. 4.9]. The moisture content of tomato reduced with drying time. An initial moisture content of 18.99% w.b was reduced to 8.41% w.b. in 420 min for 3 kg load. For 2kg and 1kg load, the moisture content reduced to 8.29% w.b. and 8.3% w.b in 360min and 300min, respectively indicating less total drying time for lesser load than the higher load to reach the moisture content [Fig. 4.9(a)]. Also, drying rate of less load was more in the beginning of drying than the higher load [Fig. 4.9 (b)]. However, drying rate was higher at the beginning for all loads and reduced at the drying proceed. It also followed falling rate period of drying.

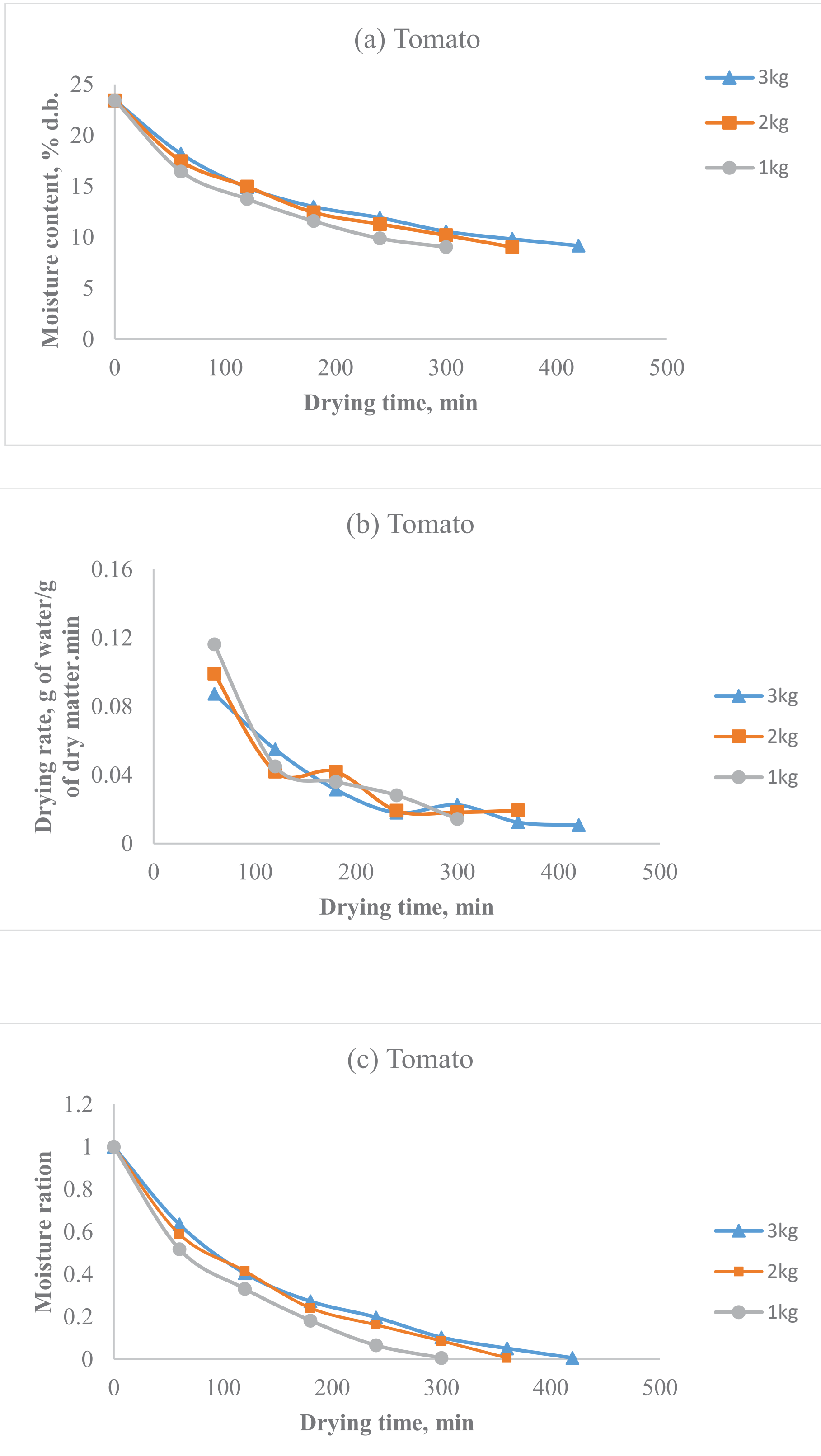


Fig. 4.9 Variation of (a) moisture content vs drying time (b) drying rate vs drying time (c) moisture ratio vs drying time at different drying air temperature for tomato seeds.

Moisture ratio vs drying time showed that the moisture ratio reduced with time [Fig. 4.9(c)]. The relationship between moisture ratio and drying time gave various models for drying kinetics. The experimental data for drying of tomato seed were fitted into the selected drying models. The model constants and the statistical parameters for drying of tomato seeds for developed dryer was evaluated (Table 4.14). Out of the three models studied, Two term exponential model was found to be the best model with R^2 0.9966, 0.9937, 0.9934 respectively for 3kg, 2kg and 1kg respectively.

Table 4.14. Evaluated model parameters for tomato seeds for performance evaluation

Model Name, tomato	Parameter values			R^2	SEE	RMSE	χ2
	a	k	n				
3kg							
Page		0.0070	1.012	0.9966	0.0028	0.0214	0.0008
Henderson and Pabis		0.0074	0.999	0.9965	0.0028	0.0215	0.0005
Two term exponential	0.0127	0.5795		0.9966	0.0028	0.0216	0.0005
2kg							
Page		0.0080	1.000	0.9935	0.0047	0.0306	0.0009
Henderson and Pabis		0.0080	0.995	0.9935	0.0047	0.0305	0.0009
Two term exponential	0.0331	0.2342		0.9937	0.0045	0.0300	0.0009
1kg							
Page		0.0100	1.003	0.9932	0.0046	0.0339	0.0015
Henderson and Pabis		0.0101	0.997	0.9933	0.0046	0.0338	0.0011
Two term exponential	0.0371	0.2646		0.9934	0.0044	0.0333	0.0012

Thus, it can be concluded that higher load required more time than the lower load capacity to reduce same amount of moisture content for all the selected vegetable seeds. Also, drying rate reduced with drying time and the rate was higher in the beginning of drying indicating absence of constant rate of drying. Drying took place in falling rate period of drying. Out of the three selected drying models, Two-Term Exponential model was found to be the best fit for all the vegetable seeds for all selected loads.

4.2.3 Dryer performance on seed Quality

Selected vegetable seeds i.e. onion, carrot and tomato were dried in the developed dryer and the performance was evaluated based on the seed quality parameters at different load. The load taken for drying were 3kg, 2kg and 1kg respectively. Seed quality parameters taken for performance evaluation were germination percentage, electrical conductivity, infected seeds, vigor index-I and vigor index-II.

The germination percentage of onion was 53±3, 50±2 and 48±2% for 1kg, 2kg and 3kg, respectively when the dryer was operated at optimized temperature of 30ºC. However, germination percentage of carrot was 85±1, 8±0 and 84±3% whereas that of tomato was 57±1, 52±4 and 78±2% at 1kg, 2kg and 3kg, respectively when the seeds were dried at their optimized temperature. The germination percentage of carrot was highest compare to onion and tomato (Fig. 4.10).

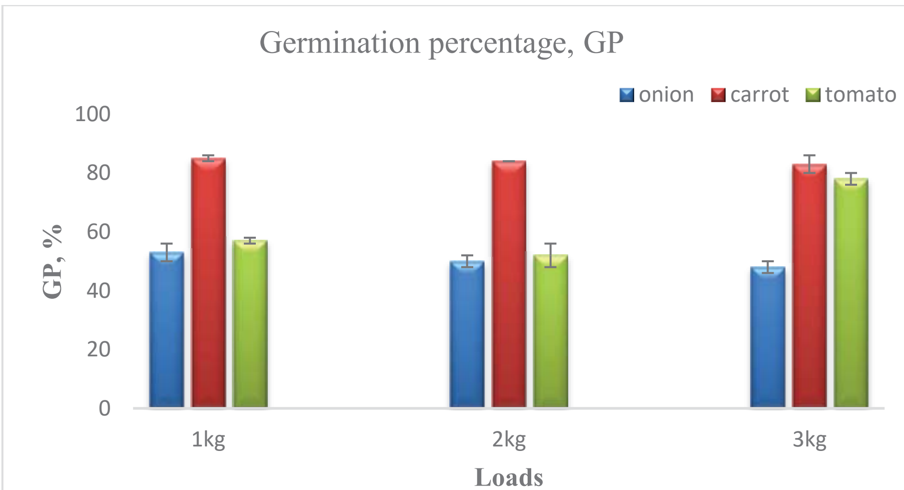


Fig. 4.10 Germination percentage of different seeds at different load

The electrical conductivity test was conducted to check the leachate in the water which revealed the potential of the seed to sustain in field conditions. The electrical conductivity of onion seed was 32.84±1.36, 40.22±3.77 and 52.45±1.43µS/cm for 1kg, 2kg and 3kg respectively. Carrot seed had electrical conductivity of 128.87±9.15, 158.3±4.05 and 131.6±7.6 µS/cm and that of tomato was 13.55±0.45, 9.77±2.34 and ±0.97µS/cm at 1kg, 2kg and 3kg respectively. Out of the three vegetable seeds, tomato has the least electrical conductivity whereas onion seeds had the maximum value (Fig. 4.11).

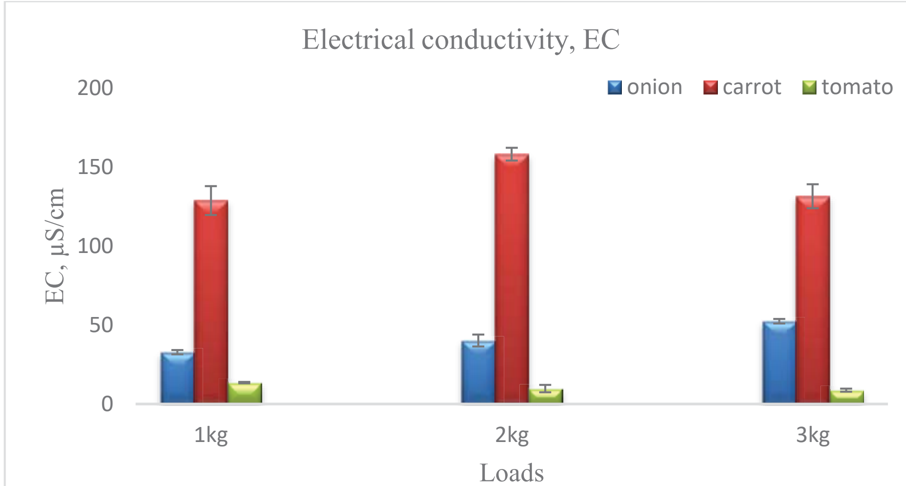


Fig. 4.11 Electrical conductivity of different seeds at different load

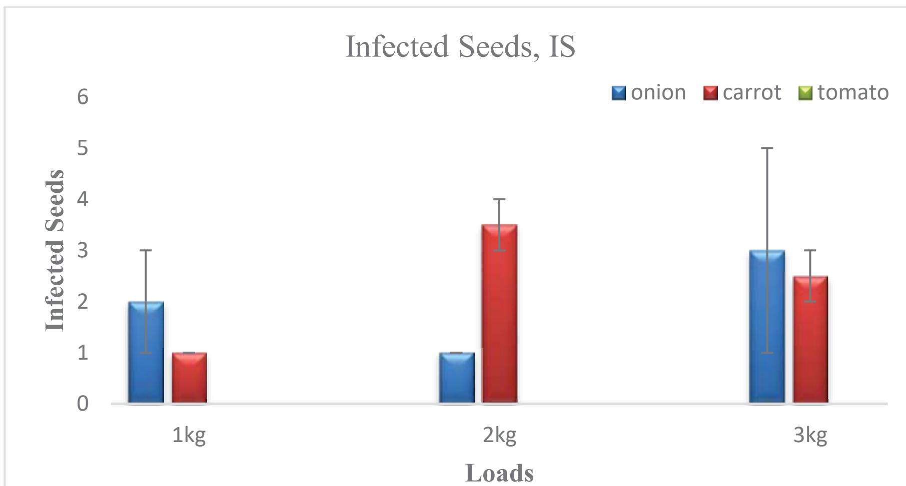


Fig. 4.12 Number of seeds infected of different seeds at different load

Number of infected seed was also checked at different load after drying. Number of infected seed ranges from 1 to 3 for onion and carrot whereas there was only one infected seed for tomato at 3kg load after drying (Fig. 4.12).

Vigor Index-I and Vigor index-II were also examined after drying for different load. Onion seed has highest vigor index-I (VI-I) of 380.8±46.26 and vigor index-II (VI-II) of 11.63±0.13 at 1kg load. The lowest vigor index of onion was observed at 2kg load where VI-I was 331.08±9.72 and VI-II was 10.6±1.4. However, carrot had maximum VI-I of 635.46±39.06 and minimum of 527.2±7.9 at 1 and 2kg respectively. But, VI-II was maximum of 19.53±1.47 at 1 kg load and minimum of 15.54±2.94 at

2 kg load (Fig. 4.14). Similarly, highest VI-I and VI-II for tomato was 580.5±12.1 and 17.92±0.32 and lowest was 575.68±5.18 and 15.88±0.22, respectively.

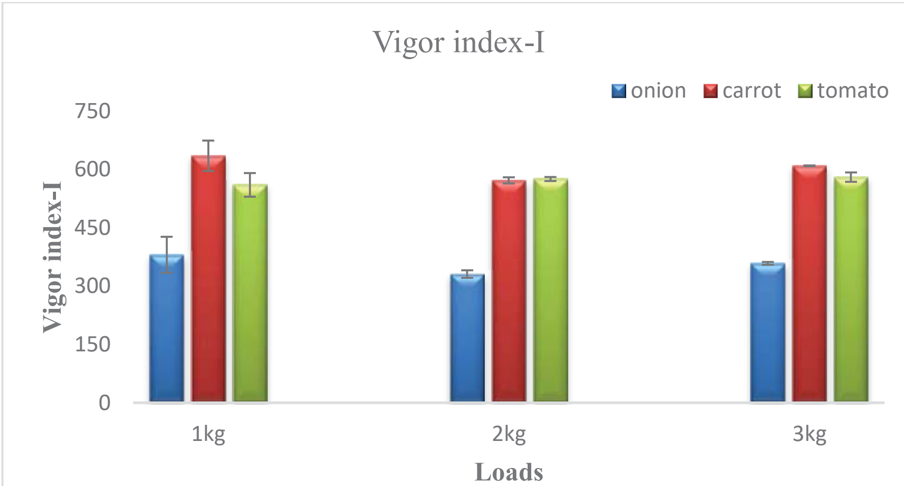


Fig. 4.13 Vigor index-I of different seeds at different load

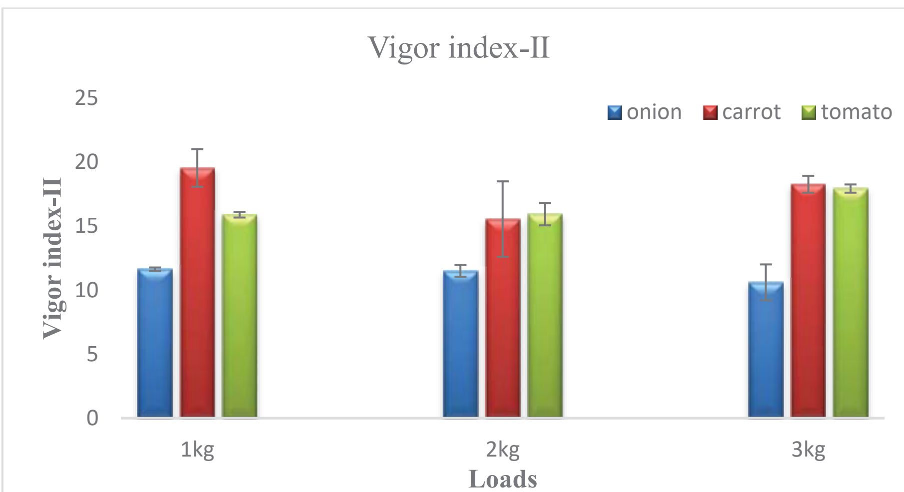


Fig. 4.14 Vigor index-II of different seeds at different load

4.3 Cost economics of developed prototype Dryer

The cost of operation of the prototype Dryer was computed according to IS: 9164-1979 **(**Annexure IV): Guide for estimating cost of farm machinery operation as explained in section 3.18 (Section 3.5.3). The final cost of the prototype, the total cost of operation per hour and cost of operation per hectare were determined. The break-even point (BEP) and payback period (PBP) of developed dryer were also estimated **(**Annexure IV**)** The variable cost the dryer was merely Rs 5/year as solar power is used as source of 75 % of annual utility hours of the dryer. The BEP (Break Even

Point) was found to be 75.2 % of annual utility of 1000 hours. The payback period was found to be 3.51 years.

Table 4.15. Cost economics of developed prototype dryer

Prototype Dryer	Mechanical
Cost of prototype, Rs.	10,000
Hourly cost of operation, Rs.	1000
Break-even point	75.2 % of annual utility of 1000 h
Pay back period, year	3.51

Chapter 5

DISCUSSION

Vegetables play an important role by providing vitamins, minerals, protein, fibre and other essential micronutrients in human dietary nutrition. Good quality seed can increase productivity of vegetables. The unit operations involved during processing of seeds are cleaning, grading, drying and storage. Out of all unit operations, drying is one of the most important and sensitive operation that may damage the quality of seeds if no proper care is taken. Unlike grains, seed are living organisms that has to maintain its quality from harvesting till the time of sowing. Drying temperature affected the quality of seed. Quality of seed deteriorates at high temperature. Therefore, it was necessary to select suitable temperature for drying. Also, precise control of temperature during drying can maintain its quality. Considering the potential of solar energy to replenish the conventional energy, it would be advantageous to use solar energy in drying. Therefore, development of solar dryer would be beneficial for the farmers as well as to the environments. Three vegetable seed (onion, carrot, and tomato) were selected to design a suitable solar drier according to the properties of seeds, and its drying kinetics. The engineering properties and drying kinetics of the selected vegetable seeds were determined to find the design values of the dryer. A temperature controller was designed for precise control of the drying temperature. The seed quality parameters i.e. germination percentage, electrical conductivity, number of infected seeds, vigor index-I and vigor index-II for all the selected seeds were measured. The performance of the dryer was evaluated in terms of drying kinetics and seed quality parameters.

The aim of this study was to design and develop solar operated dryer with precise control of temperature. The results obtained in the experiments need to be justified based on the efficiency of the dryer, quality of the seed after drying and cost economics of the dryer. This chapter presented the different rationales and reasoning regarding the results obtained in the study.

5.1 Effect of moisture content on engineering properties of vegetable seeds

Engineering properties were determined to find the design values for the development of the dryer. The effect of moisture content on different engineering properties were evaluated at different moisture level of 20, 16, 12, 8% wet basis.

The bulk density of all the selected vegetable seeds increased as the moisture content decreased. The decreasing trend may be due to the fact that increase in mass due to moisture gain was lower than the accompanying volumetric expansion of the seeds (Pradhan *et al.* , 2008).Similar decreasing trend in bulk density has been reported by Garnayak *et al.* , (2008) for Jatropha seed, Singh *et al.* , (2010) for millet and Ilori and Akinyele (2016) for amaranthus.

The increase in true density of carrot may be attributed to the relative higher mass due to moisture absorption than the volume. However, decrease in true density of onion and tomato might be attributed to increase in cell structure, higher volume expansion compare to increase in mass (Firouzi and Alizadeh, 2012).

The terminal velocity of carrot, onion and tomato increased as the moisture content increased. The increase trend of terminal velocity of all the seeds with increase of moisture content may be due to increase in mass of individual seeds. Similar trend of increase in terminal velocity with increase in moisture content was observed in cumin seed (Singh and Goswami, 1996) and hemp seed (Sacilik *et al.* 2003).

The test weight (1000 seed weight) for all the three crops increased significantly with the increase in moisture content. The increase in test weight was due to increase in moisture content (Pandiselvam *et al.,* 2014).

The sphericity for all the selected vegetable seeds decreased as the moisture increased ($p<0.05$). The decreased in sphericity with increase in moisture content showed that the increase in length is relatively more than the width and thickness.

The increased of surface area of all the seeds with increase in moisture content may be due to the fact that the size of the seed increases due to absorption of moisture. Similar trends of increase have been reported by Altuntas and Yildiz (2007) for fenugreek, Tavakoli *et al.* (2009) for soybean.

Both arithmetic mean diameter and geometric mean diameter increased with increased in moisture content. The increase in mean diameter may be due to absorption of moisture resulting in swelling of seeds.

The decreasing trend in porosity for onion and carrot may be attributed to the higher decrease in true density than bulk density whereas for increasing trend it provides an idea that decrease in bulk density is more than true density. It also indicated that the volume, shape and size increased as the seed gains moisture which creates a more intimate contact with each other, thereby reducing the pore space (Mollazade *et al.,* 2009).

The angle of repose for all selected vegetable seeds increased with the increase in moisture content. This increasing trend of angle of repose with moisture content occurs due to the reason that surface layer of moisture surrounding the particle hold the aggregate of seeds together by the surface tension (Pradhan *et al.* , 2008). Similiar trends were observed for Amaranthus (Ilori and Akinyele, 2016); cowpea (Firouzi and Alizadeh, 2012).

The increased trend of coefficient of friction with moisture content may be attributed to increase adhesion force between seeds and the surface resulting in more sticking of the materials as the moisture increased. Wood surface has the maximum coefficient of friction compare to other surfaces which indicated higher frictional force between the surface and grain. Similar trends were observed in red pepper (Üçer *et al.* 2010) , millet grain (Adebowale *et. al.* ,2012). The coefficient of friction at different surfaces helped in choosing tray materials.

5.2 Dying kinetics of selected vegetable seeds

Selected vegetable seeds were dried at different drying temperature. The moisture content of all the seeds decreased with drying time. Decreased in drying rate period of all the vegetable seeds indicated that there was no constant rate period of drying and drying occurred in falling rate period which is governed by diffusion of water in solid. Moisture ratio of all the selected vegetable seeds was also reduced with drying time. This may be due to low initial moisture content and absence of surface moisture resulting in capillary migration of water from the core to the surfaces. This needs to supply more heat to vaporize the water (Motri *et. al.*, 2013). Previous studies also revealed that drying of biomaterials is a diffusion controlled process and mostly fall in the falling rate period (Khazaei and Daneshmandi, 2007). As the drying continued, the moisture become less and require more energy to drive the remaining moisture by breaking the molecular bond of water. The energy supplied was constant resulting in longer time to break the bond and hence decrease in drying rate (Prabhanjan *et al.*, 1995). Thus, higher temperature implies larger drying force than lower temperature for heat transfer (Methakhup *et al.*, 2005; Nimmol *et al.*, 2007). Thus, it can be concluded that drying air temperature is the main parameter influencing the drying rate of agricultural products. (Touil *et al.*, 2010; Mohamed *et al.*, 2005). The drying experimental data were best fitted in Page model and Two Term Exponential model for most of the vegetable seeds based on to statistical parameters estimated i.e. R^2, $\chi 2$, RMSE and SEE value.

5.3 Optimization of drying temperature for selected vegetable seeds

All the selected vegetable seeds were dried at three level of temperature (30, 35, 40°C) and studied the quality parameters at different initial moisture content of 12% w.b., 14% w.b. and 16% w.b. respectively. The effect of temperature on seed quality parameters were studied and optimized temperature was evaluated. The optimum temperature and initial moisture content which gave the best seeds quality were 30°C and 12.04% w.b. for onion, 32.07°C and 12% w.b. for carrot and 30°C and 12% w.b for tomato. Thus, for all the temperature and different seeds studied, drying temperature of 35°C and 40°C were not suitable as it deteriorated the quality of seeds. The deterioration of seed quality may be due to thermal stress of seeds at higher temperature. The optimum temperature and moisture content obtained was also justified with the previous works (Maryam and Oskouie , 2011; Hunje *et al.,* 2007). The increased in temperature and moisture content resulted in increased of germination percentage for onion which contradicted with the theoretical concept of physiological characteristics with respect to temperature. However, it may be due to inefficiency of the processed onion seeds and uneven thermal distribution of drying air. Similarly, increase in electrical conductivity may be due to thermal stress that resulted in breakage of seed coat. This result in more leakage of solute to the water resulting in higher electrical conductivity (Maryam and Oskouie, 2011). Increase temperature resulted in increased of respiration rate and moisture content that provided a favourable conditions for the microorganism to survive. Moreover, increased in seed leachate provide a favourable environment for the microorganism to dwell. However, vigor index-I was decreased indicating less seedling length though the vigor index-II showed increasing behaviour. This showed that even the smaller seedling may have higher solid mass providing healthy seedlings and can sustain higher temperature than the seedlings of longer length.

The increased in electrical conductivity with the increase in drying air temperature for carrot showed higher loss of minerals from the seed. This also resulted in lower the solid content and hence lowering vigor index-II. However, vigor index-I was higher which showed better seedling length though germination percentage was less. This indicated better seedling growth for the seeds with less solid content of the seedlings.

Higher electrical conductivity indicated the loss of minerals due to high temperature and moisture content for tomato seeds. This also resulted in both decreasing of vigor index-I and vigor index-II. Germination percentage also reduced at higher drying temperature which was supported by better germination of tomato seeds at lower incubation temperature, Mobayen (2015). However, number of infected seeds increased at higher temperature in which microorganisms might get favorable conditions for its growth.

5.4 Design of Solar Dryer

The dryer was designed based on the drying behaviour of the selected vegetable seeds, energy required to remove the moisture and seed quality parameters. Machine designed parameters included its dimensions and selection of different units for operating the dryer. The different units were water heating units, heat transfer, air distribution, temperature control and power supply unit. Water heating units took the solar thermal energy and store in hot water storage tank in the form of sensible heat Aiswarya and Divya (2015). Sensible heat was than utilized to heat up the air through heat exchanger. Providing fan to blow hot air enabled force convection for drying. This resulted in higher drying rate. Use of temperature controller enabled precise control of temperature during drying. The temperature of the drying air was regulated precisely by circulating hot or cold water through heat exchanger, using temperature controller. Optimized temperature based on seed quality was evaluated and operated at that temperature. This helped in maintaining seed quality during drying which was the main purpose of the study. Moreover, other heat sensitive biological materials like medicinal plants and flowers which require a precise temperature range for drying can be handled by this solar dryer efficiently. The power required to operate fan, pump and control unit was supplied by solar photovoltaic energy. Thus, utilizing solar energy of both thermal and electrical source for the developed dryer was advantageous in saving and managing energy use for agriculture.

5.6 Performance evaluation and cost economics of the dryer

Performance evaluation of the developed dryer included the study of drying behavior of seeds and seed quality parameters. The dryer was loaded at three different loads i.e. 3 kg, 2 kg and 1 kg. Higher load took more time to dry than the lower load. It was due to the fact that the interaction of the hot air with seeds was less because of thicker bed compare to that of lesser load. Also, faster drying rate and higher moisture ratio at the beginning of drying showed the diffusion process of drying i.e. falling rate period. Three best model i.e. Page, Henderson and Pabis and Two-Term Exponential developed from the laboratory drying experiment were chosen. Two term exponential model was the best for the all the vegetable seeds at all load when the seeds were dried at developed dryer.

Seed quality parameters *i.e.* germination percentage, electrical conductivity, number of infected seeds, vigor index-I and vigor index-II were evaluated after the seed were dried in the developed dryer at optimized temperature. Onion and tomato seeds were dried at optimized temperature of 30ºC whereas carrot was dried at 32.07ºC of optimized temperature. Graphically, it can be interpreted that there was no specific trend in increase or decrease of quality parameters of seeds at different load. Also, less value of standard error for each seed quality parameters indicated less variability of the results at different loading rate. Also, the seed quality parameters obtained for seeds differed from one type to another. This might be due to the fact that the physiological properties of one seed differ from other and hence, independent of each other.

5.7 Cost economics

The break-even point of the dryer was 75.2% of annual utility of 1000 hours and payback period of 3.51years. Variable cost of the dryer was very merely Rs 5/year. This indicated that variable cost variable and operating cost was less as the dryer operated through solar power. As the pay-back period was less compare to the expected life of the dryer, it would be very advantageous for the farmers as they can recover their cost of investment within years.

Considering the seed quality parameters, drying behaviour of seeds and cost economics, it can be concluded that the developed solar operated dryer would be beneficial for the farmers.

Chapter 6

SUMMARY AND CONCLUSIONS

The role of vegetables on human diet is of paramount importance because of its nutraceutical properties. The demand and consumption of vegetables has been increased because of increase in population and increase of knowledge on its nutritional benefit. Therefore, it is necessary to increase the production and productivity of vegetables. Use of quality seeds can enhance the production and also make the other inputs such as fertilizers, irrigation, pesticides etc. to be cost effective. Seed processing involves various unit operations that may hamper seed quality at any stages. Since seeds are sensitive and delicate materials, proper care has to be taken during processing to maintain its quality. Drying is one of the most important unit operation that may affect seed quality mechanically as well as thermally. The temperature of drying has to be chosen wisely so as not to affect on its quality. The energy for drying may obtain from different sources such as mechanical, solar and drying beads. Among all these sources, solar energy, also being renewable energy source can be the most beneficial by utilizing both thermal and electrical power. Therefore, it is necessary to develop a solar dyer for vegetable seeds with a provision of precise control of temperature, so that it will not affect the quality during drying operation. Thus, the study was undertaken to design and develop an efficient solar operated dryer with automated temperature control by utilizing thermal and electrical power of solar energy.

A solar operated vegetable seed dryer was designed for 3kg capacity with automation of temperature control. To design and develop the solar dryer, seed parameters and machine parameters were determined. Three seeds, namely, onion, carrot and tomato were selected for the developmental study of the dryer. Engineering properties were determined at different moisture level of 8±1, 12±1, 16±1 and 20±1% wet basis. Drying kinetics was studied at different temperature of 30, 35, and 40°C. The best drying kinetics model was selected so that the drying behavior of the seeds can be found for any time within the studied temperature range. Seed quality parameters were also evaluated at different temperature of 30, 35 and 40°C and found the optimized temperature. Design values were also evaluated based on initial moisture present in seeds and amount of energy require to remove the moisture.

Accordingly, other components of the dryer were selected based on the energy required to remove the moisture, also keeping in view of maintaining seed quality and cost economics. The designed dryer was operated solely by the solar source where thermal power was obtained through solar water heater and the electrical power was obtained from solar panel. The dryer was operated at optimized temperature of 30 ºC for onion and tomato whereas 32.07 ºC for carrot seeds where the seed quality parameters were found the best. The cost economics of the dryer was also evaluated.

Based on the analysis of the results, the following conclusions could be drawn.

i) There was effect of moisture content on engineering properties of all the selected seed i.e. onion, carrot and tomato. Therefore, it was required to find the engineering properties of all the seeds from the range of harvesting moisture content (18-20% w.b.) till the safe storage moisture level (8±1% w.b). Also, it provided the designed values of seed parameters required for design of the dryer.

ii) The bulk density of carrot (0.32±0.01 g/cm^3), onion (0.45±0.01 g/cm^3) and tomato seed (0.289±0.01 g/cm^3) at 20±1% w.b. significantly increased to 0.43±0.04 g/cm^3, 0.47±0.003 g/cm^3, 0.30±0.01 g/cm^3 at 8±1 % w.b., respectively ($R^2>0.95$, $p<0.05$). True density also increased with the increased in moisture content except for the carrot seed.

iii) Terminal velocity, test weight, sphericity, surface area, geometric mean diameter, arithmetic mean diameter, coefficient of friction and angle of repose of all the selected vegetable seeds were decreased with the decreased in moisture content. Also, the porosity of carrot decreased with decrease in moisture content. However, porosity of onion and tomato increased with decreased in moisture. The effect of moisture content on engineering properties was analyzed using linear regression analysis and found significant effect of moisture on all seeds ($R^2>0.9$, $p<0.05$).

iv) Study on drying kinetics revealed that higher temperature of 40ºC required less time of 195min compare to 240min and 315 min at 30ºC and 35ºC for almost all the selected seeds. This indicated that higher temperature provide larger vapour pressure difference between the partial pressure and saturated pressure of water vapour in the drying-air.

v) The moisture evaporated from the seed decreased as the drying time increased. The rate of drying and moisture ratio decreased with drying time. The rate of decreased was higher in the beginning and reduced as the drying proceed. This showed the absence of constant rate drying period and presence of falling rate period. Thus, the drying was governed by diffusion phenomenon.

vi) Moisture ratio vs drying time curve was plotted and fitted to compare various drying models. There was exponential decay of moisture content with time and absence of constant drying rate was observed. Predicted equations for different model can be derived using model parameters, thus drying behavior of all the seed can be achieved for any time within the studied temperature range.

vii) The best model was selected according to the statistical parameters i.e, coefficient of determination (R^2), Standard error estimate (SEE) and Root mean square error (RMSE). The goodness of fit was also checked from χ^2.

viii) Out of the seven model analyzed, Page model and two term exponential models provided the best fit for all the selected seeds at different drying temperature of 30, 35 and 40°C with R^2 greater than 0.98 for all experimental conditions. Henderson and Pabis was also comparable with the selected best model.

ix) The effect of temperature and moisture content on seed quality parameters i.e. germination percentage, electrical conductivity, number of infected seeds, vigor index-I and II were evaluated. The temperature and initial moisture content was optimized based on the seed quality parameters where 30°C and 12.04% w.b. for onion, 32.07°C and 12% w.b. for carrot and 30°C and 12% w.b for tomato were obtained for best seed quality parameters.

x) The dryer was designed based on the experiment conducted on seed properties and drying behaviour of all the seeds keeping in view of precise control of temperature during drying. The designed values of the machine parameters were calculated according to the amount of moisture to be removed from the seeds and the energy required to drive out the moisture. The dryer was designed for 3kg capacity. The efficiency of dryer was 62 per cent.

xi) The dimensions of the drying chamber was (0.7x0.5x 0.82) cm with 4cm thickness of glass-wool insulation and 5cm air vent between inside and outside chamber. Different components of the dryer include air duct with hopper passage, heat exchanger for heat up the air from hot water, fan for forced convection, hot water storage tank, solar water heater, cold water storage tank and solar photovoltaic panel for supply of necessary electrical power.

xii) The dryer was in cooperated with temperature sensor cum controller with fan speed regulator. The function of the temperature controller was to cut off the pump which supply the hot water when it exceeded the set temperature. Thus, the drying temperature was precisely controlled.

xiii) The performance of the developed dryer was evaluated based on the drying kinetics and the seed quality parameters. The dryer was loaded at different loads of 1kg, 2kg and 3kg respectively. Loading of 3kg took longer drying time of 420min than 360min and 300min for 2kg and 1kg respectively to bring down the moisture content to almost at same level. Also, drying occurred in falling rate period which is governed by diffusion process.

xiv) Three best model were selected from the laboratory drying experiment and compare for the developed dryer. Two term exponential was found to be the best for all the selected seeds at all loading conditions (R^2>0.98).

xv) Seed quality parameters were also evaluated after drying the seeds at optimized temperature for different load condition. Graphically, it was observed that the load condition was independent of quality parameters.

xvi) The cost of the dryer was Rs 1, 00,000. Break-even point of the developed dryer was 75.2% of annual utility of 1000 hours and payback period was 3.51 years.

ABSTRACT

Seed are usually harvested at physiological maturity having moisture content of about 16-18% wet basis. Therefore, it is necessary to reduce the moisture content of seeds to a safe level for storage. Drying is one of the most important and sensitive unit operations in seed processing to reduce the moisture content. Hence, it is important to design efficient dryer to dry the seeds without losing its quality. Three vegetable seed (onion, carrot, and tomato) were selected to design a suitable solar dryer according to the properties of seeds, and its drying kinetics. The properties of seed studied included engineering properties and seed quality parameters. The effect of moisture content on engineering properties was studied taking the moisture range from harvesting moisture level (20±1 % w.b.) till the safe storage level (8±1 % w.b.). The relationship between moisture content and all the engineering properties studied were analyzed with linear regression and fitted well for all the selected vegetable seeds (R^2>0.90). The drying kinetics of all the three vegetable seeds was analyzed and data were fitted to several drying models to know the drying behavior of seeds. Two term exponential model was found suitable for most of the three seeds based on R^2 (0.995-0.998) values of models and their associated SEE (0.012-0.024) and Chi square (0.0001-0.0026). Also, the effect of temperature and moisture content on seed quality parameters that included germination percentage (GP), electrical conductivity (EC), number of infected seeds (IS), vigor index-I (VI-I) and vigor index-II (VI-II) were studied. Response surface methodology was employed to optimize the moisture content (12%, 14%, 16%) and air temperature (30^{0}C, 35^{0}C, 40^{0}C) for different vegetable seed. The effect of these variables on GP, EC, IS, VI-I and VI-II were determined and analyzed. Moisture content and air temperature had significant ($P<0.05$) effect on all responses. The response surface models fitted to all responses were highly significant ($P<0.001$), and had adequate precision more than 12 (>4 desirable), without having any lack of fit. Optimized parameters for drying of vegetable seeds were 12% moisture, and 30^{o}C air temperature for onion and tomato whereas 32.07^{o}C and 12% moisture for carrot seeds. Based on the designed values obtained from experiments conducted, a solar dryer was designed and fabricated. The designed dryer was of 3 kg capacity and dimensions of the dryer was (0.7 m x 0.5 m x 0.82 m) with seven number of trays. Insulation was incooperated in outside chamber to prevent heat transfer and air gap of 0.05 m was provided for air-passage. The amount of energy required was estimated depending on the moisture to be removed from the given mass of the seeds. It consisted of a solar water heater and heat exchanger, with precise control of drying air temperature through electronic circuit for automated functioning within the prescribed limits, thus utilizing both thermal and electrical solar energy. The whole system including fan, pumps and temperature controller was operated through solar panel of 400 watt. Techno-economic analysis of the developed dryer was also carried out and the efficiency of the dryer was found to be 62% for 7 hours of dryer operation to reduce moisture 20±1% w.b. to 8±1% w.b. The total cost of the dryer was estimated as Rs 1, 00,000. The breakeven point and payback period of the developed dryer was 75.2 % of annual utility of 1000 hours and 3.51 years.

सार

आम तौर पर बीजों को शारीरिक परिपक्वता पर काटा जाता है, जिसमें लगभग 16-18% गीला आधार की नमी की मात्रा होती है। इसलिए, भंडारण के लिए एक सुरक्षित स्तर तक बीज की नमी सामग्री को कम करना आवश्यक है। नमी की मात्रा को कम करने के लिए शुष्कीकरण बीज प्रसंस्करण में सबसे महत्वपूर्ण और संवेदनशील इकाई संचालनों में से एक है। इसलिए, इसकी गुणवत्ता खोए बिना बीज सूखने के लिए कुशल ड्रायर डिजाइन करना महत्वपूर्ण है। तीन वनस्पति बीज (प्याज, गाजर, और टमाटर) का चयन बीज के गुणों के अनुसार एक उपयुक्त सौर ड्रायर डिजाइन करने के लिए किया गया था, और इसकी शुष्कीकरण काईनेटीक्स । अध्ययन किए गए बीज के गुणों में इंजीनियरिंग गुणों और बीज की गुणवत्ता के मानदंड शामिल हैं। इंजीनियरिंग गुणों पर नमी की मात्रा का प्रभाव का अध्ययन किया गया था, नमी का स्तर सुरक्षित भंडारण स्तर (8 ± 1%) तक नमी आधार नमी स्तर (20 ± 1% नमी आधार) कटाई से लिया गया। नमी सामग्री और अध्ययन की सभी इंजीनियरिंग गुणों के बीच संबंध को रैखिक प्रतिगमन के साथ विश्लेषण किया गया था और सभी चयनित सब्जी बीजों (आर 2> 0.90) के लिए अच्छी तरह से लगाया गया था। सभी तीन वनस्पतियों के शुष्कीकरण की कैनेटीक्स का विश्लेषण किया गया और बीज के सूखने वाले व्यवहार को जानने के लिए कई सूखने वाले मॉडल में डेटा लगाया गया। मॉडलों के आर 2 (0.9 9 5-0.9 9 8) मूल्यों और उनके संबद्ध एसईई (0.012-0.024) और ची स्क्वायर (0.0001-0.0026) पर आधारित तीनों में से अधिकांश तीनों के लिए उपयुक्त दो शब्द एक्सपोनेंशन मॉडल उपयुक्त थे। इसके अलावा, बीज गुणवत्ता वाले मानकों पर तापमान और नमी की मात्रा का प्रभाव, जिसमें अंकुरण प्रतिशत (जीपी), विद्युत चालकता (ईसी), संक्रमित बीज (आईएस), शक्ति सूचकांक -1 (वी-आई) और शक्ति सूचकांक -2 छठी-द्वितीय) का अध्ययन किया गया। रिस्पांस सतह पद्धति को विभिन्न सब्जियों के बीज के लिए नमी सामग्री (12%, 14%, 16%) और वायु तापमान (300 सी, 350 सी, 400 सी) का अनुकूलन करने के लिए नियोजित किया गया था। जीपी, ईसी, आईएस, VI-I और VI-II पर इन चर का प्रभाव निर्धारित और विश्लेषण किया गया था। सभी प्रतिक्रियाओं पर नमी की सामग्री और हवा के तापमान में महत्वपूर्ण (पी <0.05) प्रभाव होता है सभी प्रतिक्रियाओं के लिए उपयुक्त प्रतिक्रिया सतह मॉडल बेहद महत्वपूर्ण (पी <0.001) थे, और फिट की कमी के बिना 12 (> 4 वांछनीय) से अधिक पर्याप्त सटीक था। सब्जी के बीज सूखने के लिए अनुकूलित पैरामीटर 12% नमी, और प्याज और टमाटर के लिए 30oC हवा का तापमान जबकि 32.07 औंस और गाजर के बीज के लिए 12% नमी। आयोजित किए गए प्रयोगों से प्राप्त डिज़ाइन मानों के आधार पर, एक सौर ड्रायर डिजाइन और गढ़ा गया था। डिज़ाइन किए गए ड्रायर 3 किलो क्षमता के थे और ड्रायर के आयाम (0.7 मी x 0.5 मी x 0.82 मीटर) थे, जिसमें सात नंबर ट्रे थे। गर्मी हस्तांतरण को रोकने के लिए बाहर के कक्ष में इन्सुलेशन का संचालन किया गया और हवा का मार्ग के लिए 0.05 मीटर की हवा का अंतर प्रदान किया गया था। अपेक्षित ऊर्जा की मात्रा अनुमानित बीज के द्रव्यमान से हटाए जाने के नमी पर निर्भर करता है। इसमें सौर वॉटर हीटर और हीट एक्सचेंजर शामिल था, जो निर्धारित सीमा के भीतर स्वचालित कार्य के लिए इलेक्ट्रॉनिक सर्किट के माध्यम से हवा के तापमान को सुखाने के सटीक नियंत्रण के साथ होते हैं, इस प्रकार दोनों थर्मल और इलेक्ट्रिकल सौर ऊर्जा का उपयोग करते हैं। प्रशंसक, पंप और तापमान नियंत्रक सहित पूरे सिस्टम को 400 वाट के सौर पैनल के जरिये संचालित किया गया था। विकसित ड्रायर के तकनीकी-आर्थिक विश्लेषण भी किया गया था और ड्रायर की दक्षता 7 घंटे के ड्रायर संचालन के लिए 62% पाया गया था ताकि नमी 20 ± 1% w.b कम हो सके। 8 ± 1% w.b तक ड्रायर की कुल लागत का अनुमान 1, 00,000 रुपये था। ब्रेकएव्हन बिंदु और विकसित ड्रायर की लौटाने की अवधि 1000 घंटे और 3.51 वर्ष की वार्षिक उपयोगिता का 75.2% था।

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ANNEXURE-I

A. Drying kinetics model parameters for onion seeds

Drying temp. (^oC)	Model Name	Parameter values					R^2	SE	RMSE	χ2
		a	b	c	k	n				
30, onion	Newton				0.011		0.997	0.014	0.014	0.0002
	Page				0.010	1.030	0.997	0.013	0.013	0.0002
	Modified page				0.107	0.107	0.997	0.014	0.014	0.0002
	Henderson and Pabis	1.0074			0.011		0.997	0.014	0.013	0.0002
	Logarithmic	0.7585		0.2415	139.41		0.388	0.223	0.235	0.0643
	Two term exponential	1.3838			0.012		0.997	0.013	0.012	0.0002
	Wang and Singh	-0.0079	0.00002				0.972	0.049	0.193	0.0410
35	Newton				0.014		0.996	0.018	0.017	0.0003
	Page				0.009	1.080	0.998	0.013	0.012	0.0002
	Modified page				0.118	0.118	0.996	0.018	1.811	3.7162
	Henderson and Pabis	1.0130			0.014		0.018	0.033	0.003	0.0180
	Logarithmic	0.7464		0.2536	112.39		0.359	0.258	0.234	0.0668
	Two term exponential	1.5366			0.016		0.998	0.012	0.029	0.0001
	Wang and Singh	-0.009	0.00003				0.985	0.037	0.172	0.0209
40	Newton				0.022		0.974	0.001	0.043	0.0020
	Page				0.060	0.758	0.995	0.020	0.018	0.0004
	Modified page				0.151	0.148	0.974	0.046	0.043	0.0022
	Henderson and Pabis	0.9279			0.020		0.980	0.040	0.037	0.0016
	Logarithmic	0.8073		0.1927	113.2		0.604	0.189	0.168	0.0360
	Two term exponential	0.1962			0.094		0.992	0.024	0.047	0.0026
	Wang and Singh	-0.0138	0.00005				0.874	0.102	0.102	0.0122

B. Drying kinetics model parameters for carrot seeds

Drying temp. (°C)	**Model Name**	**Parameter values**					**R^2**	**SE**	**RMSE**	X2
		a	**b**	**c**	**k**	**n**				
30, carrot	Newton				0.0138		0.9949	0.0195	0.0191	0.0004
	Page				0.0218	0.8993	0.9983	0.0115	0.0110	0.0001
	Modified page				-0.1181	-0.116	0.9949	0.0200	0.0191	0.0004
	Henderson and Pabis	0.962			0.0133		0.9965	0.0166	0.3225	0.1144
	Logarithmic	0.796		0.2040	672.95		0.3889	0.2237	0.2078	0.0500
	Two term exponential	0.110			0.1114		0.9988	0.0095	0.0090	8.9E-05
	Wang and Singh	-0.008	0.00002				0.9216	0.0781	0.0951	0.0099
35	Newton				0.0175		0.9956	0.0190	0.0184	0.0004
	Page				0.0242	0.9245	0.9973	0.0153	0.0143	0.0002
	Modified page				-0.1321	-0.132	0.9956	0.0196	0.0383	0.0004
	Henderson and Pabis	0.9706			0.0170		0.9966	0.0172	0.1387	0.0003
	Logarithmic	0.7969		0.2031	4075.16		0.4579	0.2248	0.2040	0.0505
	Two term exponential	0.5649			0.0229		0.9961	0.0184	0.0287	0.0003
	Wang and Singh	-0.011	0.00003				0.9397	0.0724	0.1049	0.0061
40	Newton				0.0237		0.9824	0.0373	0.0359	0.0014
	Page				0.0562	0.7853	0.9975	0.0146	0.0135	0.0002
	Modified page				0.1489	0.1591	0.9824	0.0388	0.0359	0.0015
	Henderson and Pabis	0.9424			0.0222		0.9865	0.0340	0.0314	0.0012
	Logarithmic	0.8174		0.1826	10173.3		0.6054	0.1917	0.1700	0.0368
	Two term exponential	0.2080			0.0925		0.9968	0.0165	0.0387	0.0018
	Wang and Singh	-0.014	0.00005				0.8795	0.1014	0.0940	0.0103

C. Drying kinetics model parameters for tomato seeds

Drying temp. (°C)	**Model Name**	**Parameter values**					**R^2**	**SE**	**RMSE**	$\chi 2$
		a	**b**	**c**	**k**	**n**				
30, tomato	Newton				0.0149		0.9958	0.0174	0.0171	0.0003
	Page				0.0237	0.8959	0.9993	0.0074	0.0072	0.0001
	Modified page				-0.1217	-0.1225	0.9958	0.0179	0.0171	0.0003
	Henderson and Pabis	0.9628			0.0143		0.9973	0.0143	0.3125	0.1074
	Logarithmic	0.8105		0.1895	2172.76		0.4101	0.2179	0.2025	0.0475
	Two term exponential	0.4025			0.0272		0.9985	0.0105	0.0102	0.0001
	Wang and Singh	-0.009	0.00002				0.9059	0.0848	0.0811	0.0072
35	Newton				0.0165		0.9953	0.0201	0.0195	0.0004
	Page				0.0185	0.9737	0.9958	0.0196	0.0185	0.0004
	Modified page				-0.1301	-0.1270	0.9953	0.0207	0.0195	0.0004
	Henderson and Pabis	0.9794			0.0162		0.9955	0.0203	0.0191	0.0004
	Logarithmic	0.7871		0.2129	4052.78		0.4300	0.2350	0.2132	0.0552
	Two term exponential	1.1860			0.0170		0.9953	0.0207	0.0313	0.0004
	Wang and Singh	-0.010	0.00003				0.9582	0.0615	0.2612	0.0773
40	Newton				0.0232		0.9972	0.0155	0.0149	0.0002
	Page				0.0312	0.9264	0.9986	0.0114	0.0106	0.0001
	Modified page				-0.1509	-0.1540	0.9972	0.0161	0.0149	0.0002
	Henderson and Pabis	0.9855			0.0229		0.9975	0.0154	0.0142	0.0003
	Logarithmic	0.8154		0.1846	5234.3		0.5460	0.2160	0.1916	0.0002
	Two term exponential	0.4971			0.0341		0.9986	0.0116	0.0152	0.0003
	Wang and Singh	-0.014	0.00005				0.9270	0.0829	0.0768	0.0069

ANNEXURE-II

A. Experimental design for optimization of seed quality parameters for onion

Onion	Responses					
Temp., ºC	mc, % w.b.	EC, µS/cm	GP, %	IS	VI-I	VI-II
30	16	13.724	75.25	3	856.139	21.9073
30	14	14.4095	76.2	2	865.671	24.9533
30	12	15.066	75.55	2	874.23	27.923
30	12	15.0366	76.15	2	873.43	27.993
30	16	13.728	74.53	3	866.913	21.073
35	14	14.939	71.4	2	833.33	25.0533
35	16	13.8123	69.8	3	806.408	23.2273
35	14	14.393	73.13	3	831.73	25.033
35	14	14.7329	72.24	2	832.237	25.533
35	12	15.9955	77.6	2	860.338	26.8793
40	12	16.544	72.45	2	846.46	25.793
40	16	13.422	62.75	3	715.404	24.473
40	14	15.3983	68.6	2	781.075	25.1533
40	16	13.824	63.56	3	714.901	24.547
40	12	16.945	73.52	2	856.246	25.593

B. Experimental design for optimization of seed quality parameters for carrot

Carrot	Responses					
Temperture, ºC	mc, % w.b.	EC, µS/cm	GP, %	IS	VI-I	VI-II
30	16	43.667	59.8587	6	10.2566	618.172
30	14	42.501	62.495	7	11.2923	633.57
30	12	41.335	65.1312	7	12.2566	658.521
30	12	40.875	67.45	6	12.3281	662.062
30	16	42.876	59.5	7	10.3281	621.032
35	14	43.3165	61	6	11.3593	620.171
35	16	43.042	61.2	6	11.0163	606.12
35	14	43.546	60.75	6	11.539	624.171
35	14	43.056	62.1	6	11.423	618.838
35	12	44.05	60.8	6	11.6991	646.964
40	12	46.765	56.7187	4	11.2992	634.954
40	16	43.147	61.9712	7	11.801	559.483
40	14	44.591	59.345	6	11.4263	606.772
40	16	42.417	61.05	7	11.5966	565.959
40	12	45.625	57.45	4	11.284	637.383

C. Experimental design for optimization of seed quality parameters for tomato

Tomato	Responses					
Temperture, ºC	mc, % w.b.	EC, µS/cm	GP, %	IS	VI-I	VI-II
30	16	10.9695	43.1418	6	14.1872	574.633
30	14	10.495	44.2	5	16.1789	621.707
30	12	9.862	48.2833	4	18.1517	668.781
30	12	9.6943	48.9772	5	17.8803	686.763
30	16	10.895	43.4887	6	14.2798	558.297
35	14	10.4748	43	7	15.6187	600.528
35	16	10.5748	41.1111	8	14.206	574.841
35	12	10.3748	46.8631	5	18.3201	613.904
35	14	10.445	43.9871	7	14.5526	573.195
35	14	10.524	43.2	8	15.6275	594.373
40	12	10.8875	44.8924	7	15.9644	559.027
40	16	10.18	39.0804	9	14.4295	577.542
40	14	10.5338	41.9864	9	15.0843	567.038
40	16	10.2861	39	10	14.1997	575.049
40	12	10.7278	44	8	15.6209	547.333

ANNEXURE-III

A. Analysis of variance for the fit of experimental data to response surface model of onion seed

Onion	Sum of Square				
Regression	**EC**	**GP**	**IS**	**VI-I**	**VI-II**
Adequate precision	31.176	24.945	6.124	47.493	45.250
R square	0.9743	0.9574	0.6944	0.9851	0.9874
Adjusted R^2	0.9673	0.9458	0.6111	0.9811	0.9840
CV %	1.31	1.42	13.18	1.05	0.80
Lack of Fit	0.8501^{ns}	0.0707^{ns}	0.5985^{ns}	0.7662^{ns}	0.0557^{ns}

B. Analysis of variance for the fit of experimental data to response surface model of carrot seed

Carrot	Sum of Squares				
Regression	**EC**	**GP**	**IS**	**VI-I**	**VI-II**
Adequate precision	25.076	24.530	11.325	33.60	51.297
R square	0.9464	0.9434	0.8169	0.9737	0.9865
Adjusted R square	0.9318	0.9279	0.7704	0.9665	0.9828
CV %	0.90	1.18	7.59	0.85	0.66
Lack of Fit	0.9608^{ns}	0.32^{ns}	0.2904^{ns}	0.0230^{ns}	0.7540^{ns}

C. Analysis of variance for the fit of experimental data to response surface model of tomato seed.

Tomato	Responses				
Regression	**EC**	**GP**	**IS**	**VI-I**	**VI-II**
Adequate precision	29.881	0.9523	17.543	27.503	15.173
R square	0.9666	0.9625	0.9090	0.9629	0.9004
Adjusted R square	0.9575	0.9523	0.8841	0.9527	0.8733
CV %	0.70	1.43	8.60	1.47	4.35
Lack of Fit	0.6653^{ns}	0.1105^{ns}	0.5055^{ns}	0.9897^{ns}	0.1198^{ns}

ANNEXURE-IV

Calculation of cost of operation of Dryer

The following assumptions were taken in to consideration while calculating the cost of operation of dryer

Assumptions:

Initial cost : Rs. 100000

Salvage value: 10 per cent of initial cost

Service life: 15 years

Annual use: 1000 hours

Fixed Cost:

Depreciation = (10,0000-10000) / (15×1000) = Rs. 6 /h-

(Salvage value of the machines as the 10% of the purchase value (IS 9164:1979))

Interest = ((100000+10000)/2) × (0.125/1000) = Rs.6.875 /h-

Insurance and taxes = (100000 × 0.02)/1000 = Rs.2 /h-

(Insurance and taxes was 2 % of the purchase price of the machine (IS 9164:1979))

Housing = (100000×0.015)/1000 = Rs.1.5/h-

Total fixed cost = 6 + 6.875 + 2 + 1.5 = Rs. 16.4/-

Variable Cost :

Repair and maintenance = (100000×0.05)/1000 = Rs. 5h/-

Total variable cost of dryer = 5 = Rs. 5/-

Total operating cost of the dryer/h = 16.4 + 5 = Rs. 21.4 /-

Annual fixed cost of of dryer = 21.4 x 1000 = Rs.21400/-

Break even and Payback period of Dryer

Annual fixed cost of operation Rs./h = 21400

BEP = Annual fixed cost / (Custom fee - operating cost)

Custom fee = (operating cos/h +operating cost/hx25% over head charges)+ 25% profit over new cost = (21.4+21.4x0.25) x 1.25 = Rs.33.43/h

BEP, h/year = 21400/(33.43-5) = 752

Payback period = Initial cost of the machine/(Custom fee-Operating cost)x Annual utility

= 100000/(33.43-5)x1000 = 3.5 years

S.No.	Dryer	
1	Cost of prototype, Rs.	100000
2	Hourly cost of operation, Rs.	21.4
3	Break even point of dryer	75.2 % of annual utility of 1000 hours
4	Pay back period, years	3.51