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Improving Vegetable Seed Quality and Dryer Performance with an Automated Desiccant-Assisted Hybrid Solar Dryer System

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ABSTRACT

A desiccant-assisted automated hybrid solar dryer was developed for vegetable seeds. The dryer consisting of two sections, one for drying the air and the other for the regeneration of desiccant. The collector area of the dryer is 1.3 sq.m and three trays of 0.18 m^2 of area each in the drying chamber. The dryer consists of a real-time data acquisition system for recording the temperature, and humidity, and the dryer was equipped with an automatic temperature control unit to maintain the temperature at a preset level(≤40°C). The bottom of the drying chamber was also filled with desiccant for continuous drying after sunshine. The performance of the developed dryer was evaluated by drying fresh onion seeds having an initial moisture content of 18-20% (wb) and compared with the developed dryer without desiccant considering both the drying parameters and quality parameters of the dried seeds. The developed dryer with desiccant was found to produce a significant difference in drying rate (P<0.0001) for onion seeds compared to dryers without desiccant drying. All the quality parameters in terms of germination percentage, and vigor index I and II, found to have a significance difference (P<0.0001) compared to without desiccant drying. The developed solar dryer provides a promising alternative for the continual drying of other materials including onion even after sunshine hours with real-time data acquisition system and also found to be superior in retaining quality.

Keywords: *Desiccant, Drying rate, Solar dryer, Onion seed, Germination, Vigor*

INTRODUCTION

Seeds, crucial for agricultural processes, are typically harvested at physiological maturity with a moisture content ranging from 18-22% on a wet basis. This moisture level is necessary to prevent seed-shattering losses. However, the elevated moisture content poses a risk to seed quality, promoting mold growth, susceptibility to pests and insects, and increased respiration during storage [20].

To mitigate these losses, it is imperative to reduce the moisture content to a safe level, prompting the need for suitable drying methods. Various drying techniques, such as air drying, sun drying, solar drying, hot air oven drying, microwave drying, freezing drying, infrared drying, and vacuum drying, exist. Unfortunately, most of these methods require advanced machinery, a stable power supply, skilled personnel, and permanent installations, making them impractical for smallholders in developing countries [3] [9]. An alternative and promising energy resource, particularly in regions abundant with sunlight, is solar energy [13]. Solar drying systems, particularly in tropical and subtropical countries, stand out as attractive applications of solar energy [6].

However, the weather-dependent nature of solar radiation necessitates backup or stored energy to sustain the drying process during periods of insufficient sunlight. Addressing this challenge involves coupling solar dryers with energy storage materials that accumulate excess energy during sunny periods and release it when solar energy is unavailable [11] [10]. One innovative solution is the desiccant-assisted solar drying system, which has the potential to dry agricultural products during off-sunshine hours by storing thermal energy and facilitating air dehumidification. Solid clay-based composite desiccant materials emerge as cost-effective options that enhance moisture adsorption capacity [19]. To preserve seed quality, including germination rate, viability, and vigor, drying must occur at low temperatures and humidity. This requirement aligns with the capabilities of desiccants [13] [5]. In the pursuit of advancing sustainable practices within agricultural processing, with a specific focus on drying applications, our study aimed to contribute to this vision. We undertook a comprehensive investigation to develop an efficient desiccant-assisted solar dryer, specifically designed to address the unique requirements of seed drying. This initiative seeks to not only enhance the overall sustainability of agricultural processes but also to optimize seed preservation and quality during the crucial drying phase.

MATERIALS AND METHODS

The development of the desiccant-assisted automated hybrid solar dryer at the Division of Agricultural Engineering,

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ICAR-IARI, followed a systematic process that began with the meticulous selection of materials and continued with the design of the drying chamber. To obtain the optimum operating condition of the desiccant-assisted automated hybrid solar dryer, the developed dryer was evaluated at three different levels of desiccant seed ratio D1 (0.25:1) D2 (0.50:1) D3 (0.75:1), and airflow rate A1 (0.038 m^3/s), A2 (0.064 m^3/s), A3 (0. 090 m^3/s) for the selected seeds. For optimizing the dryer different conditions like overall drying rate and total drying time, thermal efficiency, germination percentage, vigor index I and vigor index II were calculated. The optimized condition was set in the dryer and the comparative study was done for the drying of fresh seeds in the developed dryer with desiccants, dryer without desiccants based on parameters like drying rate and drying time, thermal efficiency, germination percentage, vigor index I and vigor index II. To assess and evaluate the dryer's performance, the Pusa Red variety of onion seeds was chosen. The dryer was optimized to handle 3 kg of the selected Pusa Red variety of onion seed, with seedbed depths ranging from 5-7 mm. This range of depth aligns with the recommended depth for onion seed drying, as specified by the International Rice Research Institute. Considering the maximum bulk density of 500 kg/m^3 of the selected variety of onion seeds at harvesting moisture content, i.e., at 20 percent [13].

Bulk Density = Weight of material (kg) / Volume of bulk material (m^3) Design values for the collector area of the solar dryer were established by carefully considering the selection of the tilt angle and the collector surface area to optimize solar insolation. The aim was to find the ideal angle that would enable the solar collector to absorb the maximum amount of solar energy efficiently. This optimal tilt angle ensures that solar radiation strikes the surface perpendicularly, maximizing energy absorption. The determination of the tilt angle (β) for the solar collector was based on the methodology outlined by [2]. The angle of tilt of solar collector $\beta = 10^0 + \text{lat } \phi$, Where, lat ϕ is the latitude of the collector location. New Delhi lies along the latitude of 28.70°N. Hence, the suitable value of β used for the collector was calculated as: $\beta = 10^0 + 28.7^0 = 38.7^0$. The value of insolation for New Delhi i.e., the average value for global horizontal irradiance (H) on a horizontal surface is 5.2 kWh/m^2, and taking into consideration 7.35 hours of average annual bright sunshine, the value of insolation for Delhi is 706.89 W/m^2. The average effective ratio of solar energy falling on a tilted surface to solar energy falling on a horizontal surface R is given by: R=1.0035×H. Therefore, the value of the effective ratio of solar energy (R) becomes R = 1.0035 × 706.89 = 709.36 W/m^2 [2] [15]. For determining the mass flow rate of air by considering the average air velocity, the height of the air gap was taken as 6 holes each of 1 cm i.e (1 x 6) cm = 0.06 m and the collector width was assumed to be 0.61 m. The volumetric air flow rate was calculated by using the formula

$V'_a = V_a \times$ air gap height × width of collector and mass flow rate of air calculated by using the formula, $m_a = V_a \times \rho_a$ where density of air (ρ_a) = 1.28 kg/m^3. Therefore, m_a= 0.0046× 1.28 = 0.00589 kg/s. The area of the collector was determined by the following equation,

$$A_c = \frac{m_a \times C_P \times \Delta T}{\eta \times R}$$

where, Ac = Area of collector, m^2, m_a= Air flow rate, kg/s, Cp Specific heat of air, J/kg K, ΔT = difference between ambient temperature and drying temperature, °C, η = Thermal efficiency in fraction, R = average effective solar insolation on tilted surface, W/m^2. Hence, the length of the collector was calculated as,

$$L = \frac{A_c}{\text{width of collector}} = \frac{0.51}{0.46} = 1.13 \text{ m} \sim 4 \text{ feet}$$

So, the area of the collector for heating the air and regeneration of desiccant was calculated by the same procedure. The overall collector area of the solar dryer for air heating and desiccant regeneration was taken as 1.2 m x 1.05 m (4 ft. X 3.5 ft). The drying cabinet comprises four essential components: the basic frame, the drying chamber, trays, and loading/unloading doors. The dryer's dimensions and energy requirements were determined based on the moisture content that needed to be reduced in the onion seed to reach a safe moisture level. To prevent heat loss to the surroundings, Polyurethane (PUF) Insulation was incorporated within the drying chamber. The drying chamber's size was established at 80 cm in length and 65 cm in width. The designed capacity of the dryer was set at 3 kg, and for seed drying, a bed thickness of 7 mm was adopted for onion seeds. The size of (0.6 m x 0.3 m) was kept to fit inside the chamber and the height of the tray was maintained at 3 cm, whereas the gap between the two trays was kept at 5 cm for ease of handling. The number of trays was calculated using the given formula:

$$\text{Number of trays} = \frac{\textit{Mass of the product}}{\textit{Area} \times \text{Thickness } \textit{of seed bed} \times \textit{Density of seed}} = 4$$

The initial moisture content was calculated by using the hot air oven method. Amount of moisture to be removed (m_w) from the product was calculated by the equation $m_w = m_p \frac{m_i - m_f}{100 - m_f}$,

where, mi= initial moisture content of the seeds (%), m_f = final moisture content of the seeds (%), mw-mass of water to be removed (kg), and m_p = initial mass of the product (kg). So, m_w= 0.45 kg [21] [14].

The moisture to be removed from 3 kg of onion seed for bring down to the safe moisture level of 6% was found to be 0.45 kg. The amount of heat needed to expel the moisture from the onion seed $Q = m_p c_p \Delta T_p + m_w h_{fg}$, where, m_p =Mass of the product kg, c_p= Specific heat of product, kJ/kg-K ΔT_p = Change in temperature before and after heating the product (°C), ta-tp m_w = Mass of water to be removed, kg, h_{fg} = Latent heat of vaporization, kJ/kg.

$$c_p = \left(\frac{m_w}{100}\right) \times c_{pw} + \left(\frac{100 - m_w}{100}\right) \times c_{pd}$$

where, c_{pw} = Specific heat of water (4.18 kJ/kg K), c_{pd} = Specific heat of dry matter (1.463-1.881 kJ/kg K), Therefore, c_p = 2.341kJ/kg K [16].

The amount of heat required is the function of the temperature and moisture content of the product. The latent heat of vaporization h_{fg} = 4.186 (597 – (0.56 (t_p+273)) =1800kJ/kg [14].

The following three solid desiccants silica gel, bentonite clay, and activated carbon were selected for the development of composite desiccant and evaluated based on performance, regeneration rate absorption rate, and low overall cost. Based on the preliminary experiment, it was found that the performance of the composite desiccant (silica gel 100% bentonite clay 0%, activated carbon 0%), was better among all set of composite desiccants. So, this composite desiccant was selected for further use in the solar dryer as an assistant. All the functional units of the dryer were fabricated and assembled to develop the dryer. The optimum design values for the collector area of the solar dryer for air heating and desiccant regeneration designed were found to be 1.2 m x 1.05 m (4 ft. X 3.5 ft), dimensions of inside of drying chamber (0.65× 0.35× 0.75m) containing 4 trays of area 0.6m × 0.3 (Fig 1). Quantity of heat required for drying was found out to be 1800kJ/kg. An automated system was developed for continuous measurement of temperature, humidity and maintained the temperature inside the drying chamber (< 40^0C). Five DHT-22 temperature and relative humidity sensors were used for the measurement and recording of temperature and relative humidity of ambient air, air inside the drying chamber, exhaust air, solar collector air and of air inside the regeneration chamber. Automation of the controller unit was programmed through an Arduino Mega 2560 microcontroller board with Tmega 2560 microcontroller chip. The temperature control unit was based on a comparison of existing temperature to the desire preset temperature value. If the temperature crossed the preset value, the thermoelectric cooler peltier module was brought in action until the temperature reached the preset value. Thus, it maintained and controlled the temperature inside the drying chamber.

Thermal efficiency of the desiccant assisted solar dryer encompasses the attributes of the amount of moisture removed and the temperature rise that is developed in the desiccant assisted solar dryer as a result of solar radiation. Thermal efficiency was calculated as:

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

where Mw is, amount of moisture removed from the seeds; Hv, latent heat of vaporization of water at drying temperature T_d; Total airflow in the drying chamber Ms; Specific heat of ambient air Cs, (1.005 + 1.88 × H) kJ/ kg °C; Ambient relative humidity of the air H, Average drying air temperature in the dryer Td, and Ts, the temperature of ambient air [17]. Germination test and seed vigor index-I (SVI) and seed vigor index-II (SVII) were conducted on pure seed fraction using 50 seeds in three replications of selected varieties of onion seeds. The test was conducted following the between paper method and keeping at 25±10 °C temperature and 93±2% relative humidity as per ISTA (2021). Seed Vigor indices were estimated following the procedure suggested by the [1]. Vigour indices were computed by multiplying the germination percentage and seedling length/seedling dry weight. Seedling vigour index I = Germination (%) × Seedling length (cm) Seedling Vigor index II = Germination (%) × Seedling dry weight (mg). Statistical software SAS was used to analyse the experimental data with completely randomized design and factorial randomized block design and then optimise the operating conditions for the dryer.

Fig 1: Experimental setup of the developed desiccant-assisted automated hybrid solar dryer

RESULTS & DISCUSSION

The peak ambient temperature occurred during the time frame from 2 pm to 2:30 pm. The relative humidity of the surrounding air reached its maximum during the morning hours and gradually declined to its lowest point between 3:30 pm and 4:00 pm. After 4 pm, there was an observable upward trend in ambient air relative humidity.

Effect of desiccant-to-seed ratio and air flow rate on drying rate: The treatment combination that exhibited the highest drying rate (3.49% m.c./h) was characterized by a desiccant-to-seed ratio of 0.75:1 and an air flow rate of 0.09 m^3/sec. Conversely, the lowest drying rate of 2.22% m.c./h was observed when employing a desiccant-to-seed ratio of 0.25:1 and an air flow rate of 0.038 m^3/sec, in comparison to the other treatment combinations (Figure 2). Analysis of variance demonstrated the significant influence of both the desiccant to seed ratio and the air flow rate on the drying rate (P<0.0001). The interaction between the desiccant-to-seed ratio and the air flow rate also exerted a substantial impact on the drying rate. By transitioning the desiccant to seed ratio from 0.25:1 to 0.5:1, the drying rate notably increased from 0.081 to 0.096 kg/h. Nevertheless, when further raising the desiccant to seed ratio to 0.75:1, the subsequent increase in drying rate was found to be statistically insignificant (0.099 kg/h). Similarly, elevating the air flow rate from 0.038 to 0.064 m^3/s led to a significant escalation in drying rate, from 0.074 kg/h to 0.1004 kg/h. With a further increase in air flow rate to 0.090 m3/s, the drying rate increased to 0.1024 kg/h, which was found to be non-significant at a 5% level of significance.

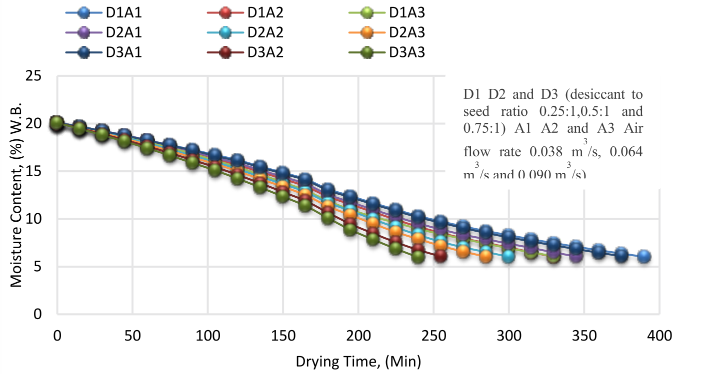

Fig. 2: Drying rate curve at different levels of desiccant and airflow rate

This shows that a higher air flow rate resulted in higher moisture carrying capacity per unit of time, thus facilitating a higher drying rate of the onion seeds. This showed that the residence time reduced with increased air flow and thus drying rate was affected. Hence, the intermediate air flow rate of 0.064 m^3/s was found optimum for the operation of the dryer. The similar results were reported by [12]. It could be inferred that the desiccant to seed ratio of 0.5:1 was optimum for the developed dryer. The rate of drying was found to be significantly higher in the fabricated dryer (0.0967 kg/h) as compared to the dryer without desiccant (0.0668 kg/h). Thus, there was a significant effect of the dehumidification produced by the desiccant in the dryer which ultimately led to increase in the overall drying rate. The higher drying rates in the desiccant-assisted dryer were also reported by [4].

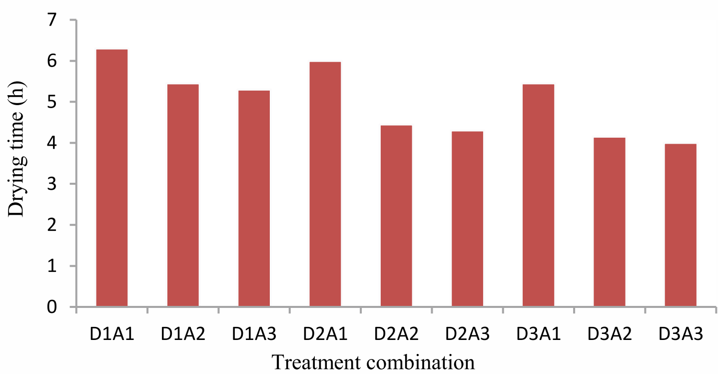

Fig.3: Drying time of onion seed at different desiccant-to-seed ratios and airflow rates

Effect of desiccant to seed ratio and air flow rate on drying time: The lowest drying time of 4 h was observed for desiccant to seed ratio of 0.75:1 at 0.09 m^3/sec air flow rate (D3A3). The longest time duration of 6.3 h for drying of onion seed from 20 to 6 percent was observed for desiccant to seed ratio of 0.25:1 and airflow rate of 0.038 m^3/s (D1A1) Fig.3. As the desiccant to seed ratio changed from 0.25:1 to 0.5:1, the drying time reduced from 5.6 to 4.7 hours. However, with a further increase in desiccant to seed ratio from 0.5:1 to 0.75:1, the decrease in drying time was non-significant (4.6 hours). Similarly, drying time decreased significantly from 5.9 to 4.6 hours with an increase in air flow rate from 0.038m^3/s to 0.064m^3/s. Nevertheless, further increase in air flow rate to 0.090 m^3/s, resulted in the reduction of drying time to 4.5 hours, which was non-significant at a 5% level of significance. Analysis of variance showed that the drying time of onion seed was significantly affected by different levels of desiccant to seed ratio and air flow rate (p<.001). The drying time was inversely proportional to the drying rate and a higher drying rate of resulted in reduced drying time. The drying rate was found to be optimum with an airflow rate of 0.064 m^3/s and desiccant to seed ratio of 0.5:1. Hence, the drying time was accordingly standardized/ optimized for the treatment. Further, the optimum air residence time at a higher inlet air flow rate of 0.064 m^3/s and sufficient moisture absorption capacity at 0.5:1 desiccant-to-seed ratio accounted for lower drying time. The time required to remove the excess moisture in case of control (without desiccant) was 6.55 h was higher as compared to dryer with desiccant at 5.22 h. The analysis of data revealed that the drying period of seed in dryer with and without desiccant were significantly different (P<0.0001).

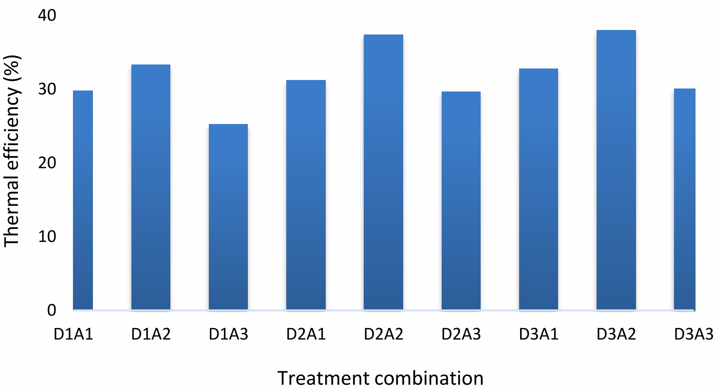

Fig. 4: Thermal efficiency of solar dryer at different desiccant to seed ratios and air flow rates

Effect of desiccant to seed ratio and air flow rate on thermal efficiency: Similarly, the thermal efficiency of dryer increased significantly from 31.9 to 36.2 per cent with an increase in air flow rate from 0.038 to 0.064 m^3/s. However, the thermal efficiency of dryer decreased significantly to 30 percent with further increase in air flow rate to 0.090 m^3/s, at a 5% level of significance Fig.4. The optimum inlet air flow rate resulted in a higher gradient between saturation and absolute humidity of the drying air, thus enhancing the carrying capacity of evaporated moisture and accounted for higher values of thermal efficiency. Furthermore, any increase in flow rate was not necessarily able to cause adequate temperature differences, which resulted in increased thermal efficiency. These results were in conformity with the findings of [18]. The higher thermal efficiency of the dryer was observed at desiccant to seed ratio of 0.75:1. Thus, a significant interaction effect of inlet air flow rate (0.064 m^3/s) and 0.50:1 was observed on thermal efficiency.

The analysis of variances revealed a significant difference (P<.0001) in the thermal efficiency of the dryer within the desiccant-assisted automated hybrid solar dryer as compared to the drying without use of desiccant conditions. Effect of desiccant to seed ratio and air flow rate on germination percentage: The germination percentage ranged between 64 - 72, the highest and lowest being observed at 0.5:1 desiccant to seed ratio with 0.064 m3/sec air flow rate and 0.75:1 desiccant to seed ratio with 0.090 m3/sec air flow rate, respectively Fig.5. The ANOVA for germination percent revealed a significant effect of desiccant to seed ratios (P < 0.001) as well as air flow rates (P <0.001). The interaction of desiccant-to-seed ratios and air flow rates also significantly affected germination percentage. As the desiccant to seed ratio was altered from 0.25:1 to 0.5:1, the germination was enhanced from 69.6 to 70.7 percent.

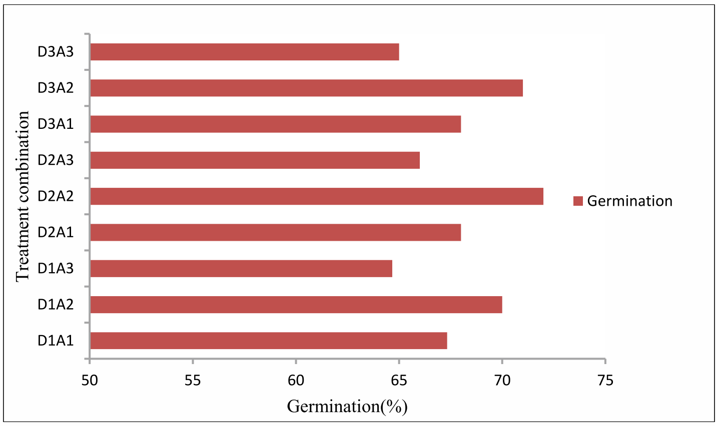

Fig. 5: Germination percentages of onion seed at different desiccant-to-seed ratios and airflow rates

However, with a further increase in desiccant to seed ratio from 0.5:1 to 0.75:1, the germination per cent decreased (67.33%) significantly. Similarly, germination per cent increased significantly from 69.1 to 70.4 with an increase in air flow rate from 0.038 to 0.064 m^3/s. However, with a further increase in air flow rate to 0.090 m^3/s, the germination per cent declined to 67.3, which was significant at 5% level of significance. At higher drying rates, the seed coat of some of delicate seeds shrinks or split and becomes impermeable to moisture. However, inner part of seed remains moist. The seeds become hard and are more prone to infestation by insect pests and diseases. The embryo of the seed may also get damaged due to rapid drying and may lead to desiccation induced damage [8]. The onion seeds dried with and without a desiccant-assisted solar dryer were evaluated for germination percentage and significant differences in germination % were observed the mean germination in case of onion seeds dried in desiccant assisted solar drying was 70 percent, which was significantly higher as compared to without desiccant assisted drying (67 %). Effect of desiccant to seed ratio and air flow rate on Vigor Index I, Vigor Index II: The vigor index I vigor Index II ranged between 874.61 to 1140.39 and from 1971.70 to 2313.90, respectively, clearly indicates a substantial variation in vigor across the different treatment conditions. The highest and lowest values were found at specific combinations, namely a desiccant to seed ratio of 0.5:1 with a 0.064 m^3/sec air flow rate and a desiccant-to-seed ratio of 0.75:1 with a 0.090 m^3/sec air flow rate (Tab.1).

Treatments combination	Vigor Index I	Vigor Index II
D1A1	909.60	2004.70
D1A2	976.29	2081.60
D1A3	888.92	2010.60
D2A1	956.35	2051.35
D2A2	874.61	1986.60
D2A3	1140.39	2313.90
D3A1	930.70	2047.35
D3A2	992.40	2091.45
D3A3	875	1971.70
C.D (P = 0.05)	34.55	62.14

Tab.1: Effect of seed treatments (desiccant to seed ratios and air flow rates) on the Vigour Index I Vigour Index II of onion seeds

The analysis of variance (ANOVA) conducted on both Vigor Index I and Vigor Index II revealed highly significant effects of both desiccant-to-seed ratios ($P < 0.001$) and air flow rates ($P < 0.001$). Specifically, when the desiccant to seed ratio was increased from 0.25:1 to 0.5:1, both Vigor Index I and Vigor Index II exhibited an improvement, with values increasing from 909.60 to 956.35 and from 2004.70 to 2051.35, respectively. This suggests that a moderate increase in the desiccant to seed ratio can have a positive impact on vigor. However, a noteworthy observation was made when the desiccant to seed ratio was further increased from 0.5:1 to 0.75:1. In this case, both Vigor Index I and Vigor Index II decreased significantly, with values of 930.70 and 2047.35. This decrease may be attributed to diminishing returns or potential adverse effects associated with excessively high desiccant to seed ratios. The study revealed significant findings regarding the drying process and its efficiency. Specifically, increasing the air flow rate from 0.038 to 0.064 m^3/s markedly accelerated the drying rate, though diminishing returns were observed beyond this point. Notably, the highest thermal efficiency, reaching 38.03%, was achieved at an airflow rate of 0.064 m^3/s, combined with a desiccant-to-seed ratio of 0.75:1. Moreover, the developed dryer, equipped with a microcontroller-based Peltier system, effectively controlled drying chamber temperatures below 40°C, making it adaptable for seed drying across various crops. In a notable achievement, the desiccant-assisted solar dryer demonstrated a remarkable germination percentage of 71% when utilizing a desiccant-to-seed ratio of 0.5:1 and an airflow rate of 0.064 m^3/s. ANOVA results underscored the substantial influence of desiccant-to-seed ratios and air flow rates on Vigor Index I and Vigor Index II, with highly significant p-values (<0.001). In a comparative analysis between the desiccant-assisted solar dryer and conventional drying methods without desiccant, the former showcased superior results with a thermal efficiency of 32%, a high germination rate of 70.22%, a shortened drying time of 5.22 hours, and an increased drying rate of 0.0967 kg/h. In contrast, the values for drying without desiccant were notably lower at 27.16%, 67%, 6.55 hours, and 0.0668 kg/h, respectively. These findings emphasize the clear advantages of the desiccant-assisted approach for efficient and effective seed drying.

Future scope of the study

Future research could explore the optimization of the desiccant-assisted automated hybrid solar dryer for a wider variety of vegetable seeds and other agricultural products. Investigations into alternative desiccant materials and configurations might enhance the dryer's efficiency and effectiveness. Additionally, integrating advanced data analytics with the real-time data acquisition system could provide deeper insights into the drying process, potentially leading to further improvements in drying rates and quality retention.

Authorship Contribution Statement: Each author made substantial contributions to the conceptualization, methodology, data collection, and analysis, as well as the writing and editing processes of this research article.

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