1. Introduction

1.1 Background of the study

Rural farmers in India are constrained by their limited resources, and hence they face a significant challenge in dealing with the high moisture induced post-harvest losses of crops and food materials. A regular or frequent use of drying machineries for the reduction of moisture as a post-harvest intervention is constrained by the capital and operational costs. An inexpensive and easily operable solar drying solution for drying of these agricultural produces at a minimized cost holds a potential to positively impact the situation for these farmers. The development of such a solar drying should ensure achieving an adequate air temperature, its control and proper circulation [1].

At present India is the world's fifth-largest economic power, where agriculture and the associated sectors accounting for 20% of its GDP. This sector includes a variety of activities such as land preparation, irrigation, crop development, harvesting, and food processing. To fulfil the present energy demands in Indian agriculture, renewable solar energy has emerged as a key energy source. Application of solar energy in water pumping, refrigeration, distillation, desalination, and drying are proving to be more efficient than the traditional energy sources. Researchers are now focussing on improving the performance and cost-effectiveness of solar-powered systems [2,3].

A solar dryer facilitates utilization of solar energy to produce the thermal energy and, if required, mechanical energy for effective removal of moisture from wet materials including crops. Hence, solar dryers for crop drying is a sustainable approach for reduction of food loss by the use of renewable energy sources and without causing harm to the environment [4]. Solar radiation being available for free of cost and environmental-friendly, it is an ideal form of energy source for low-cost drying of crops [5,6].

The open sun drying (OSD) system is the most primitive form of the use of solar radiation for crop drying. However, it results in a low intensity drying requiring an extended drying time. This leads to the vulnerabilities such as exposure of the crops to the enzymatic degradation due to an extended wet-phase. Additionally, OSD exposes the crops to contamination from pests, wind-blown debris, and precipitation. The indirect solar dryer (ISD) is preferred over OSD as it specifically tackles the limitations associated with the OSD [7].

The utilization of solar energy in greenhouses to dry agricultural products is a milestone in solar drying. It is an effective, low-cost, renewable, and sustainable technology in the agricultural crop processing sector for rural farmers [4]. Greenhouse dryers are characterized as direct solar drying with the greenhouse cover for capturing the solar radiation for producing warmer air for drying. Also, the cover works as the protective cover against possible contaminations from pests, wind-blown debris, and precipitation. A relatively faster rate of drying protects the crop from the vulnerability of degradation and spoilage [5,8–10]. Numerous research studies have explored the effectiveness of solar greenhouse dryers for drying food crops in diverse climatic conditions worldwide [3,11].

For drying of agricultural crops, solar greenhouse dryers are operated in mixed mode also. This is due to their ease and lower cost of construction as compared to other types of dryers. It works by collecting and absorbing sunlight using a solar collector, which then heats up the air that flows through the drying chamber. The drying chamber contains trays where the crops is placed, allowing the warm air to circulate the food and effectively dry it. By utilizing this process, greenhouse dryers can efficiently dry and preserve various types of crops and food products [8,12]. Solar greenhouse dryers run in active mode to increase the greenhouse's efficiency are reported for drying fish, fruits, vegetables, oil seeds, cereals, grains, and other foods [5,8–10].

By nature, the availability of solar power is not necessarily continuous and uniform as the solar radiation intensity in a day is affected by the hour of the day and the extent of cloud-covering at the instant. Due to the intermittent nature of solar power the option of thermal storage is utilized which assumes a critical role in enhancing performance within solar energy systems. Methods based on sensible heat and latent heat storage are integral for optimizing solar energy utilization. Sensible heat storage (SHS) involves elevating the storage medium temperature, proving to be a simpler and more cost-effective energy storage approach with notable technological and economic advantages over phase change energy storages. Packed beds, featuring loosely arranged solid material through which a heat transport fluid circulates, emerge as ideal storage units for air-based solar systems.

On the other hand, phase change materials (PCMs) like paraffin, provides the abilities to store and release thermal energy at nearly constant temperatures, with few additional advantages such as high heat capacity, reduced volume requirements. This renders PCMs, with their diverse temperature-transitioning range, particularly appealing for efficient thermal energy storage in greenhouse applications [11,13,14].

Integrated solar greenhouse drying systems are developed combining the features of the greenhouse drying and benefits of thermal storage systems, offering a relatively efficient and sustainable approach to drying agricultural crops. These systems are proving to be useful for the farmer and pharmaceutical industries in drying various crop commodities during the winter and off-sunshine hours. Solar radiation is harnessed to heat the air inside the greenhouse, which in turn raises the temperature of the product intended for drying. Subsequently, the moist and cooled air. utilizes the heat available from supplementary thermal storage systems when the solar radiation does not heat it up to the set conditions. Integrated solar greenhouse dryers with enhanced dryer performance are reported in various forms, viz., (i) assisted with solar air heater [9,12,15], (ii) use of photovoltaic (PV) module for air circulation [8,16], (iii) PCM as latent heat storage material [13,17–19]. The present work aimed at developing a parabolic structured solar greenhouse drying system integrated with (i) corrugated plate type solar air heating with PCM (corrugated SAH with PCM), (ii) air-circulation system powered by a photovoltaic (PV) module and (iii) sensible heating storage system placed inside the drying dome for the primary processing of ginger, as its first objective. Various other options such as evacuated tube heat pipe [4,20,21] and biomass based pre-heating [22–25] were not considered as the proposed solution is a low-cost and robust solution for small and rural farmers.

Ginger is popular worldwide as a spice, flavouring agent, and medicinal ingredient. India is the leading producer, accounting for about 43.81% of the world’s total production [26]. Both forms of ginger, i.e., fresh and dried ginger, are used for consumption. Ginger has nutritional qualities, including the presence of essential oil, oleoresin, starch, gums, proteins, carbohydrates, and fiber [27]. Ginger cultivated in the northeastern region of India has been reported to possess higher quantities of oil and oleoresin compared to ginger grown in other regions of the country. However, the market for dried ginger products in India has not yet been fully developed, and therefore, appropriate technological interventions are needed to obtain stable products through primary/ secondary processing [28].

When agri-food commodities are subjected to drying, mathematical modelling techniques facilitates estimating the drying time requirement, as any over-drying of the produce may cause loss of food value. In case of ginger, researchers have tested multiple mathematical models sourced from literature against experimental drying data. Best fit models was then selected to predict the drying kinetics of ginger [27,29]. Similarly, the application of artificial neural network (ANN) is also attempted for having a better and more efficient management of crop drying. Although the feed-forward neural network improves the accuracy of the mapping of output-based input parameters, very few literature is available on ANN based prediction for processing operations or product quality in ginger [30,31]. In this work, empirical models as well as ANN model were chosen to apply for drying of ginger under different systems with improved predictability [28]. Antioxidant properties, rehydration and shrinkage characteristics, essential oil content, microstructural properties and textural characteristics were proposed to be included for the description of the quality outcome of the dried products in the second objective of the work.

The progression of drying and changes in quality parameters during drying is dependent on the exposure of temperature and air velocity around the crops. Researchers have used computational fluid dynamics (CFD) based analysis for profiling of temperature and air velocity within drying chambers. Also, researchers have conducted energy analyses to assess the efficiency of solar air heaters (SAH) in relation to variations in mass flow rate and climatic conditions. Several studies have delved into energy analysis within SAHs. The objective of such an analysis is to create a more efficient system by minimizing the inefficiencies. Energy and exergy efficiency assessments are reported for various food material drying processes [13,15,32]. The profiling of temperature and air velocity within drying chamber of the ISGHD system and energy and exergy analysis of the ISGHD process as a whole were undertaken as the third objective.

The effectiveness of solar greenhouse dryers is dependent on weather, sunshine hours, and intensity of solar radiation. As Northeast India is known for having location and climate specific difference in these factors, there is a need for crop-specific studies on the feasibility of solar greenhouse drying of ginger in the region. Along with prediction of performance, the economic feasibility and sustainability of a dryer is also essential to be evaluated for economic, energy, and environmental factors. Economic considerations involve analyzing the aspects like payback period, dryer expenses, and the cost of drying products. Energy-related parameters entail examining the energy embodiment and specific energy usage of the dryer. Environmental assessments concentrate on CO_2 emissions, CO_2 reduction measures, and carbon credit accrual. By assessing these variables, a more comprehensive understanding of the dryer's sustainability and economic viability can be gained [14]. This aspect was aimed to be addressed through the fourth objective.

Overall, this research aims to develop a sustainable, parabolic structured integrated solar greenhouse drying (ISGHD) system and to examine how it performs in comparison to other low-cost techniques for drying ginger in the northeastern region of India. The research will include the study of drying kinetics, energy, and exergy analysis, mathematical modelling, ANN modelling, and investigations into the quality of ginger dried in a solar greenhouse drying system. The ISGHD system is expected to facilitate ginger drying in controlled conditions and contribute to small and rural farmers' income.

1.2 Research gap

In the Northeast region of India, farmers and pharmaceutical industries encounter significant challenges with crop drying during the winter months and periods of limited sunshine. Considerable research has been undertaken in the field of greenhouse dryers, focusing on leveraging forced convection to improve performance. However, formidable obstacles such as thermal energy storage and economic feasibility persist. The climatic parameters specific to the region, such as solar radiation, temperature, wind velocity, and relative humidity, underscore the need for a comprehensive investigation into the effectiveness of solar greenhouse drying (SGHD). Despite the wealth of studies on forced convection methods, there remains a notable gap in understanding the effectiveness of SGHD in the distinct climate of the Northeast region. Addressing this gap could potentially unlock sustainable and cost-effective solutions for crop drying, benefiting both agricultural practices and industrial processes in the region.

1.3 Objectives

1. To develop an integrated solar-air-heating system for greenhouse drying of agricultural produces
2. To standardize the operational parameters of the integrated solar greenhouse drying (ISGHD) for ginger drying based on the product quality
3. To simulate the thermal performance of ginger drying in the developed ISGHD
4. To study the environmental and economic sustainability of ginger drying in ISGHD

1.4 Justification

1. Solar greenhouse drying is an efficient and cost-effective sustainable method for drying products. Integrated solar greenhouse drying is beneficial for the farmer and pharmaceutical industries for drying agricultural commodities, including ginger, during the off-sunshine hours and in winter.
2. Optimized operational parameters are likely to facilitate the production of good quality dried ginger products using only renewable energy sources with a drying rate comparable to the existing forced convection dryers.
3. The exergy and energy efficiency of operating the ISGHD system for ginger drying is to quantify its contribution to sustainability.
4. The feasibility and sustainability of a developed product for commercial-scale adoption depend significantly on factors such as cost and environmental impact.

1.5 Arrangement of thesis

The thesis is divided into five chapters for an orderly and logical presentation of the work done and its findings.

Chapter 1: This chapter already discussed above gives a summary of the introductory view of our proposed idea and brief literature supporting the work. The chapter extends to a discussion on the research gap, including a section on its scientific justification, followed by the objectives of the research work.

Chapter 2: This chapter consists of the literature review of the work that has helped in a better understanding of the concept of the topic.

Chapter 3: This chapter discusses the materials used and methods implemented for accomplishing the objectives.

Chapter 4: This chapter illustrates the results obtained from following the methodologies of the 4 objectives and presents the inferences made from those results.

Chapter 5: This chapter gives a summary of the complete work and concludes the thesis.

1.6 Summary of chapter I

This chapter provides an overview of the introductory perspective on our proposed concept and a concise review of literature relevant to the creation of an integrated solar greenhouse drying (ISGHD) system designed for drying agricultural produce. The drying system is equipped with a solar air heater (SAH), phase change material (PCM), and PV module to enhance its efficiency. The discourse delves into crucial aspects such as drying kinetics, modelling methodologies, and quality criteria specific to ginger. Special attention is given to thermal analysis and effectiveness assessments carried out to evaluate the dryer' efficiency. Further, the chapter underscores the importance of environmental considerations and cost evaluations linked to the newly devised solar greenhouse drying system, particularly regarding its suitability and advantages for rural farmers.