Experimental analysis of the characteristics of soybean seed using a fluidized bed dryer

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Abstract

Continuous advancements in product quality and cost reduction have driven manufacturers to enhance soybean meal, the crucial protein source for human and animal nutrition worldwide. In this study, our primary objective was to conduct experimental investigations on soybean meal drying using a fluidized bed dryer, aiming to ascertain drying kinetics and the impact of various parameters such as temperature, drying agent velocity, mass flow rate, bed length, and bed height on the drying process. Through a series of meticulously controlled experiments, we discovered that the drying rate of soybean meal exhibits an upward trend with increasing inlet air velocity and temperature. Additionally, the mass flow rate of soybean proved to be inversely proportional to the drying capacity of the fluidized bed dryer, meaning that as the mass flow rate increases, the drying capacity decreases. Furthermore, we observed that the fluidized bed dryer attained maximum efficiency when operated at the initiation of the drying process, emphasizing the crucial role of temperature. Surprisingly, the height of the particle bed and the speed of the drying agent did not yield significant influences within the range of experimental conditions explored.

Keywords: Soybean, Fluidized Bed Dryer, Moisture Content, Mass Flow Rate, Drying Rate.

Introduction

Soybean meal, a vital component in the soybean production chain, serves as the primary and crucial source of protein for animal feed formulations, contributing approximately 65% of the total protein utilized in formulating diets for various livestock species such as poultry, sheep, goats, pigs, and cattle.[1] Over the past four years, global soybean meal production has experienced a notable surge of approximately 14%, with Brazil witnessing a particularly remarkable increase, reflecting the dynamic nature of the local shops for this important item. Consequently, the production of soybean meal, as in other sectors, is primarily about producing a high-quality product while minimizing production costs. The quality of soybean meal is primarily determined by the specific conditions employed during the drying process. Effective drying techniques reduce moisture content to safe levels, inhibit microorganism growth, extend product shelf life, and reduce costs associated with transportation and storage. To meet market demand, soybean meal must meet specifications that call for a moisture content of about 14% (dry basis) after the drying process.[2]

Soybeans and soy-based products have gained immense importance in the market as they provide a plant-based alternative to meat and dairy products. The inclusion of soy products in the daily diet greatly improves the absorption of important vitamins, calcium, magnesium, iron and fiber. It is crucial to ensure that the storage and transportation of soy products do not result in nutrient loss due to excessive moisture. When soybeans are stored with high moisture levels, there is a heightened risk of spoilage and germination. Compared to corn, soybeans possess a higher oil content, making them more susceptible to spoilage. Therefore, it is imperative to thoroughly dry soybeans before storing them. The application of heat plays a vital role in deactivating nutrient-hostile properties and enhancing the overall quality of soy-based products.[3]

Drying, the ancient technique of removing water from food, serves as the oldest known method of preserving food and involves various processes, such as sun drying or artificial drying, predominantly applied to nature’s bounty. While the main goal of drying is to preserve food, reducing the moisture levels in nature’s bounty also results in diminished expenses related to packaging, storage, and transportation.[4] This is achieved by decreasing the weight and size of the end product, leading to cost savings. Additionally, the process of dehydration not only prevents the growth of microorganisms responsible for spoilage and decay but also eliminates the necessity for refrigeration during handling. Moreover, it enables the convenient creation of product mixes for retail purposes. With the ongoing enhancements in the quality of dried foods and the increasing importance of prepared and convenient products, the potential for dried nature’s bounty is now more promising than ever. The manufacturing of dried nature’s bounty involves diverse processes, primarily differing in the chosen drying method, which is influenced by the specific food type and desired qualities of the final product. Broadly speaking, the process of fruit drying involves several steps. Initially, pre-drying treatments are carried out, which may include actions like selecting fruits of appropriate size, removing peels, and preserving their natural color.[5] The subsequent stage involves the actual drying process, which can be achieved using either natural or artificial methods. Finally, after the drying is complete, post-drying treatments come into play. These treatments may involve sweating the fruits, inspecting their quality, and packaging them appropriately. Various commercially available moisture removal methods exist, moreover the optimal pick depends on quality requirements, characteristics of the raw materials, and economic considerations.[6]

In the seed processing industry, seed drying emerges as a crucial post-harvest operation with distinct requirements compared to grain drying due to the specific quality expectations for the final product of the drying process. Moving bed dryers, on the other hand, offer more uniform drying conditions due to the continuous movement of the seeds. Among the moving bed dryers, concurrent, counter-current, and cross-flow dryers are widely used. Each type of dryer has its advantages and disadvantages, depending on factors such as seed type, desired drying rate, and energy efficiency requirements. Proper selection of the dryer type is crucial to achieve high-quality and uniform drying of seeds.[7] However, moving beds alleviate this issue by constantly altering the position of the drying material during the process. These methods are commonly referred to as low drying rate methods, as they typically require longer drying times. Nonetheless, they are widely recognized worldwide because the dried seeds must exhibit optimal field emergence and germination upon sowing. The Canadian Food Inspection Agency is responsible for administering the Canada Seed Act, which establishes a seed classification system aimed at effectively communicating seed quality. Seed varieties are subject to specific standards outlined in Schedule-I of the regulations, commonly referred to as grade tables. For example, the soybean seed grade standard mandates a minimum germination rate of 65-85 out of 100 for seeds to be classified as seed grade. Previous studies conducted by Felipe and Barrozo focused on soybean seed drying using a concurrent bed dryer, where they developed empirical equations to assess various quality traits such as germination, vigor, and cracking after the drying process. Additionally, Barrozo investigated soybean drying techniques utilizing counter-current and cross-flow moving bed dryers. Additionally, Souza conducted fixed bed drying experiments with soybean seeds, analyzing the quality variations among different positions within the fixed bed, revealing non-homogeneity in seed quality.[8]

Convective drying stands out as an efficient drying method widely employed across diverse industries, including agriculture, food processing, bio-oil production, building materials, chemical and ceramic manufacturing, paper production, textiles, and even nuclear waste disposal. While numerous studies have been conducted on convective drying of moist materials, both experimental and numerical investigations require additional effort and attention. Convective drying relies on various factors such as air velocity, temperature, humidity, and uniform air flow. Ensuring these external factors remain within desired conditions presents a challenging task during experimental setups. Furthermore, modeling convective drying poses difficulties due to the intricate nature of drying kinetics. Extensive literature contains a wealth of experimental and numerical studies addressing convective drying of moist materials.[9]

In this comprehensive review, both theoretical and experimental aspects of fluidized bed (FB) drying are examined in relation to different agricultural products. The review considers important parameters including product type, drying temperature, airflow speed, initial moisture content, specialized drying techniques, and post-drying storage conditions. By considering these critical factors, a comprehensive understanding of the application of FB drying in agriculture can be achieved.[10] While there are multiple static drying methods documented in the literature, this study solely focuses on FB drying techniques, highlighting their unique advantages, diverse applications, and potential limitations, including attenuation. To evaluate the impact of operating conditions on moisture content, airflow speed, relative humidity (RH), temperature, and product quality, a comparative analysis is conducted, contrasting FB drying with conventional solar drying. The subsequent section discusses the outcomes derived from these comparisons. Through an extensive literature review, it becomes evident that FB dryers have demonstrated considerable success in drying various agricultural products, encompassing fruits, vegetables, grains, and leaves. Furthermore, most test results endorse the utilization of FB drying methods for optimal outcomes.[11]

An in-depth investigation was conducted to analyze the drying behavior of soybeans using a fluidized bed (FB) dryer, incorporating varying temperatures, air velocities, and bed heights. A comprehensive framework was created by integrating drying rate equations and quality models to establish optimal strategies for fluidized bed (FB) drying. This framework takes into account crucial factors including quality criteria, drying capacity, energy consumption, and drying cost. By considering these key elements, the framework enables the determination of effective and efficient FB drying strategies. Notably, very high temperatures moreover air velocities were found to induce increased cracking and decreased rehydration levels due to elevated internal stress within the soybeans.[12] However, the protein content remained unaffected by these variables. To ensure the preservation of soybean integrity, end moisture content of 23.5% (dry basis) has identified as the safer threshold to prevent excessive cracking. Remarkably, the implementation of higher temperatures and air velocities within the full range resulted in a substantial reduction in drying time, from 380 to just 50 minutes. An interesting finding was that air velocity had no significant impact on the bulk density and shrinkage of soybeans. Through simulation-based analysis, the optimal operating parameters for fluidized bed drying of soybeans were determined as follows: a drying air temperature of 140 °C, a bed depth of 18 cm, a drying air fluidization velocity of 2.9 m/s, and an air recirculation rate of 90% to ensure efficient heat conservation.[13]

The objective of the study was to examine the efficiency of superheated steam and hot air drying techniques in fluidized bed (FB) dryers for inhibiting the activity of the urease enzyme in soybeans. During the experiments, it was observed that the moisture content and temperature had a positive relationship with the effective diffusion coefficient and inactivation rate constant for both heating mediums. Optimal outcomes were obtained by subjecting soybeans to temperatures between 135 and 150 °C using hot air, and 135 °C with superheated steam. These conditions facilitated the desired inactivation of the urease enzyme while maintaining protein solubility and lysine content within the desired range. Interestingly, the choice of heating medium did not affect the overall quality of the soybeans, as the rapid inactivation of the urease enzyme occurred before protein denaturation could occur.[14]

By implementing a pretreatment step prior to FB drying, the overall grade of soybeans underwent significant enhancements. The utilization of near-infrared radiation in combination with fluidized-bed drying demonstrated a remarkable effectiveness in minimizing the occurrence of cracking and breakage in soybean kernels.[15] This positive outcome can be attributed to the reduced stress experienced by the grain kernels during the drying process, ultimately leading to the production of a higher-quality product. A comprehensive analysis was conducted to examine the effects of near-infrared radiation power, air velocity, air temperature, and grain bed depth on cracking, breakage, color, and microstructure of soybean grains. This study involved extensive investigations to assess the impact of different conditions on these characteristics. Promising results were achieved when near-IR radiation powers of four and six kW were employed, leading to optimal levels of cracking and breakage within an acceptable range. Moreover, this approach showcased improvements in the physical quality of the soybean grains, including enhanced protein solubility and a reduction in urease activity.[16]

In a study conducted by Luz, a tray dryer was used to examine the drying process of soybean meal. The findings revealed that the drying primarily occurs during the decreasing rate period, indicating that diffusion within the particles limits the mass transfer step.[17] Similar observations were reported by Park, who noted that the decreasing rate period is commonly observed in the drying of agricultural products and foods. During this stage, the main transport mechanisms include liquid diffusion, capillary flow, and vapor diffusion. In the context of food drying, diffusion is recognized as the primary mechanism for moisture migration within the solid, especially within pores and small spaces saturated with vapor or liquid. In industrial settings, indirect rotary dryers are typically employed for soybean meal drying, although they are known for their high energy consumption, leading to increased operational costs and environmental pollution due to heating and pollutant emissions.[18] In order to tackle these difficulties, a combined equipment solution like the DTDC (Dessolventizer-Toaster-Dryer-Cooler) can be employed for industrial drying of soybean meal, with the dryer component utilizing fluidized bed technology. Fluidized bed dryers have become increasingly popular for drying applications in the food industry, as well as for porous materials and solid waste in various processing sectors. When compared to other drying methods, fluidized bed dryers offer several advantages, including higher drying rates and improved heat and mass transfer rates between phases. These advantages contribute to an overall enhancement in process efficiency. Several researchers, including Liebanes and Meziane, Srinivasakannan and Balasubramanian, and Murthy and Joshi, have investigated the application of fluidized bed drying in different contexts, such as olive pomace, ragi (Eleusinecorocana), latermillet, and Aonla (Emblicaofficinalis) drying. In these studies, fluidized bed drying consistently demonstrated superior results with regards to reduced time of the drying as well as the production of higher-quality final products.[19]

In a research investigation, the drying process of grass seeds was examined using three different drying methods: conveyor belt drying, stable bed drying, and FB drying. The results reveals the drying kinetics and seed quality remained largely unaffected when using stable bed and FB drying at temperatures of thirty as well as fifty °C. Numerous analyses have focused on exploring dryers of high drying rate while preserving germination potential. Drying seeds using microwaves posed a challenge, as continuous microwave operation hindered seed germination. However, intermittent operation proved to be effective in reducing drying time while preserving seed quality. Compared to fixed bed drying, fluidization and semi-fluidization at low speeds offered the advantage of shorter drying times and maintaining bed homogeneity without compromising seed quality.[20] Fluidized bed (FB) drying has been successfully applied to various seeds, including soybeans, terebinths, pumpkin seeds, beet seeds, wheat, and rice. When both wheat and rice were dried using fluidized bed and spouted bed dryers, it was observed that the fluidized bed dryer exhibited higher drying rates, while the spouted bed dryer demonstrated lower energy consumption. Both drying methods yielded seeds with good germination potential. The preference for either the spouted bed dryer or fluidized bed drying depended on the desired temperature range, with the former being favored at higher temperatures and the latter at lower temperatures. In a separate study conducted by Clemente, grape seeds were dried in a stable bed under various temperatures of air moreover velocities using ultrasound. The findings indicated that ultrasound did not have a significant impact on the grape seeds' drying kinetics.[21] Considering the insights gained from these studies and the proposed hypotheses, the primary objective of this analysis is to investigate the drying kinetics of soybeans using three different drying techniques: fixed bed drying, FB drying, and microwave-assisted FB drying.

Experimental Setup

A fluidized bed dryer with a single-phase electric motor of 1 kW, 900 rpm, a centrifugal fan with four heating coils of 1 kW each, fluidized bed in addition to a perforated sheet has developed for experimental purposes. The fluidization chamber has provided an inlet and outlet for soybean. A duct has also been attached from the top of the fluidization chamber to the centrifugal fan so that the utilization of hot air exit out from the fluidization chamber could be possible. Specifications of fluidized bed and perforated plate are given in Table 2.1.

Table 2.1 Specifications of Fluidization Chamber

Sr. Nos.	Specifications	Values
1	Length of Bed in meters	0.42
2	Width of Bed in meters	0.085
3	Height of Bed in meters	0.28
4	Number of holes in perforated plate	1824
5	Perforated plate thickness in mm	0.6
6	Hole diameter (mm)	2

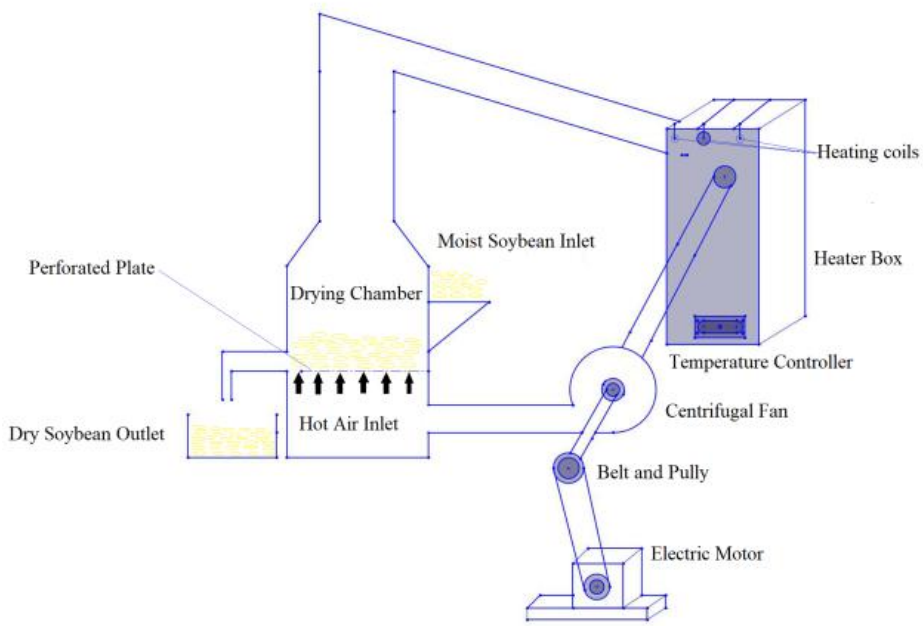

Figure 2.1 Illustrative sketch of a fluidized bed dryer

Materials and methods

Soybean from Uttar Pradesh, India was used for drying experiments. Seeds initial moisture content measured by a moisture meter. The initial moisture content of the soybean seeds came out to be 26.86 % (db). The mean diameter of the soybean sample seeds was 6.5 mm computed utilizing a micrometer screw gauge. The soybean sample submerged in clean water for twenty four hours. Then the sample of 1 kg soybean seeds has placed in the domestic fridge at a temperature of 5 to 8 ºC for 4 to 6 days to achieve equilibrium. Sample soybean packed in a sealed plastic receptacle. After that the sample has taken out from the domestic refrigerator and put the sample soybean at atmospheric temperature for at least twenty four hours prior to experiment.

Table 3.1 Soybean properties and conditions

S. No.	Parameter	Value
1	Density of soybean ρ_s (kgm^{-3})	1101
2	Density of gas (air) ρ_a (kgm^{-3})	1.235
3	Soybean diameter d_s (mm)	5 to 8
4	Initial soybean temperature (°C)	28
5	Initial soybean moisture content (db) ($kgkg^{-1}$)	0.36
6	Minimum fluidization velocity u_{mf} (ms^{-1})	1.5 to 3.0
7	Air temperature T_a (°C)	40, 45, 50
8	Bed mass of soybean (kg)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0
9	Superficial air velocity u_a (ms^{-1})	5.9, 6.7, 7.7

Results and discussion

Table 4.1 Comparison of various operating conditions

Atmospheric Humidity H_{atm} ($kgkg^{-1}$)	X_{Si} (%)	Ta_i (°C)	W_m ($kghr^{-1}$)	Soybean Outlet Parameters		Air Outlet Parameters			Efficiency (%)	Resistance Time (min)
				Xs_o (%)	Ts_o (°C)	Ta_{oavg} (°C)	RH (%)	H_{oavg} ($kgkg^{-1}$)		
0.0143 (T_{atm} = 28 °C, RH = 51 %)	26	44.0	40	13.93	41.23	39.65	27.4	0.0153	15.57	76.63
	26	44.6	41	13.94	41.68	40.11	26.8	0.0152	15.26	75.15
	19	44.0	205	13.98	40.54	38.18	28.9	0.0153	22.48	18.37
	19	45.0	210	13.95	41.47	39.05	27.8	0.0158	21.42	17.23
	31	44.0	40	15.82	41.00	39.14	27.1	0.0155	19.43	76.63
	31	44.0	26	13.94	42.00	40.43	26.0	0.0154	14.82	77.48
0.00826 (T_{atm} = 22 °C, RH = 51 %)	26	44.0	55	14.06	40.97	39.00	16.4	0.0096	11.23	59.18
	31	45.0	34	14.00	42.00	40.05	15.5	0.0094	10.34	90.34
0.02449	26	44.0	23	13.95	41.44	40.43	45.1	0.0254	42.99	128.8

(T_{atm} = 42 °C, RH = 51 %)	31	44.0	15	13.97	41.54	40.32	45.1	0.0252	48.00	129
0.01978 (T_{atm} = 32 °C, RH = 71 %)	26	44.6	32	13.96	41.84	40.51	36.3	0.0206	12.14	131
	31	44.0	20	14.05	41.42	39.02	37.0	0.0208	12.67	132.6

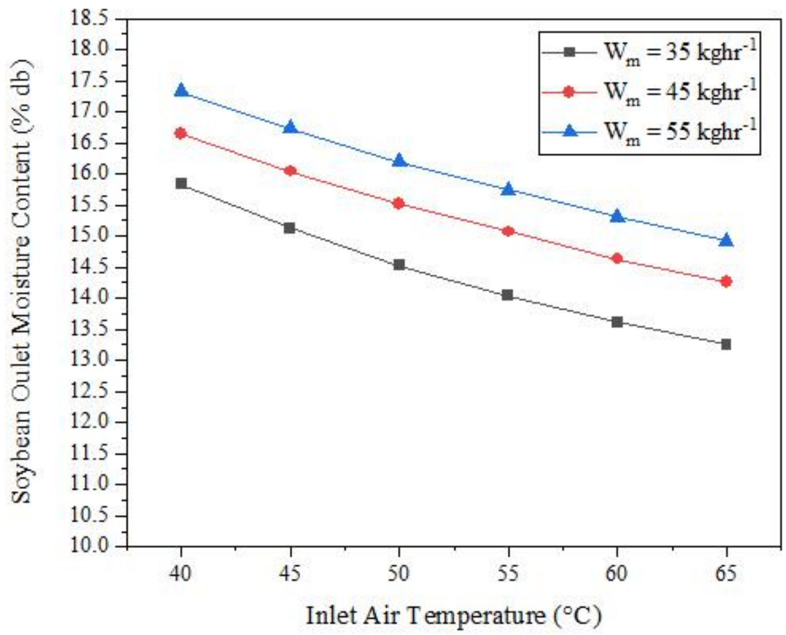

Figure 4.1 Variation of outlet moisture content of Soybean versus temperature of inlet air at three different flow rates

Figure 4.1 shows the relation between outlet moisture content of soybean and temperature of inlet air. Blue color curve represents the moisture contents of soybean when the mass flow rate of soybean kept 35 $kghr^{-1}$. Red color curve represents the moisture contents of soybean when the mass flow rate of soybean kept 45 $kghr^{-1}$. Black color curve represents the moisture contents of soybean when the mass flow rate of soybean kept 55 $kghr^{-1}$. All the three curves follow the same pattern. As the temperature of inlet air is increased, the moisture contents for all the three mass flow rates are also decreased.

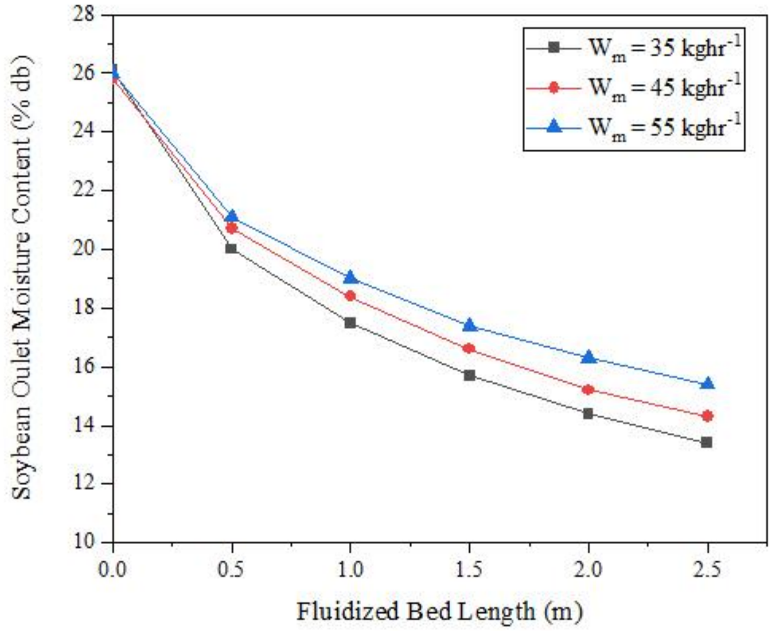

Figure 4.2 Variation of outlet moisture content of Soybean versus fluidized bed length at three different flow rates

Figure 4.2 shows the relationship between content of soybean and fluidized bed length. Blue color, red color and black color curves represent the moisture contents of soybean when the mass flow rate of soybean kept 35 $kghr^{-1}$, 45 $kghr^{-1}$ and 55 $kghr^{-1}$ respectively. The same pattern has been followed by all the three curves. As the fluidized bed length is increased, the moisture contents for all the three mass flow rates are also decreased. At the starting of bed length there is a significant change in the moisture content afterwards the change in the moisture content was decreasing with further length of bed.

The relation between humidity of average air outlet and temperature of inlet air is shown in Figure 4.3. The behavior of outlet air humidity for three mass flow rates is shown in three different colors (Red, Blue and Black). In spite of increase in temperature of inlet air, the values of average air outlet humilities are increased because air has taken the moisture from the soybean inside the fluidization chamber.

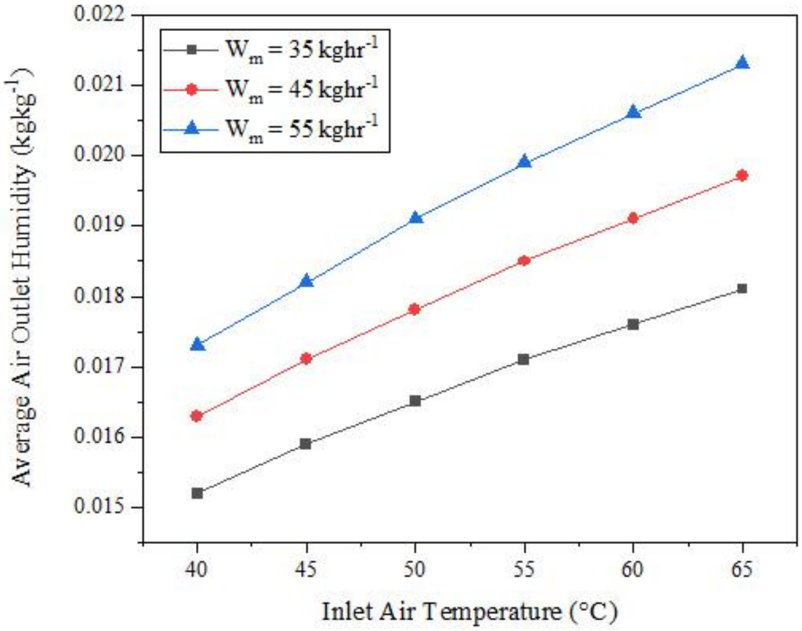

Figure 4.3 Variation of humidity of average air outlet versus temperature of inlet air at three different flow rates

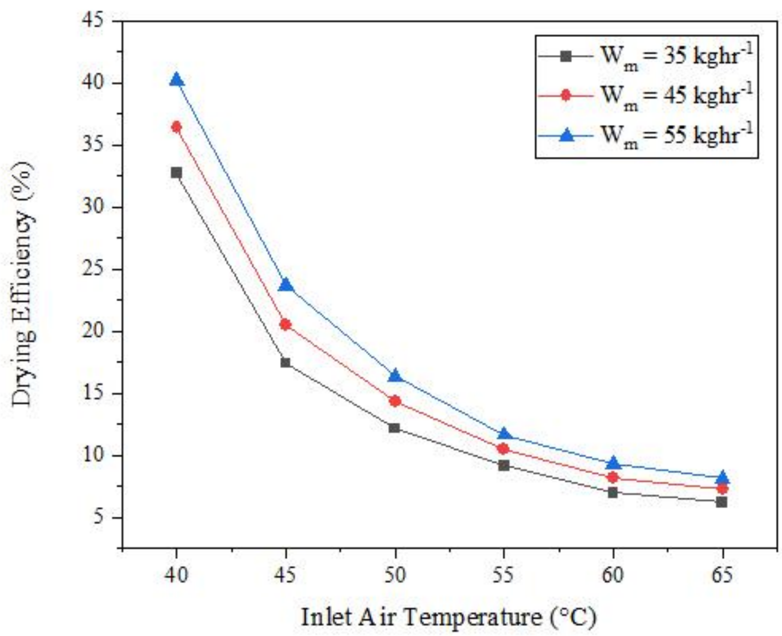

Figure 4.4 Variation of drying efficiency versus temperature of inlet air at three different flow rates

From the figure 4.4, it is obvious that at low inlet air temperature, the drying efficiencies are very high for the three mass flow rates of 35 $kghr^{-1}$, 45 $kghr^{-1}$ and 55 $kghr^{-1}$. From 40 °C to 45 °C, there is high fall in the drying efficiency of the fluidized bed dryer. After that there is a gradual decrement in drying efficiency with the increment of every 5 °C of inlet air temperature.

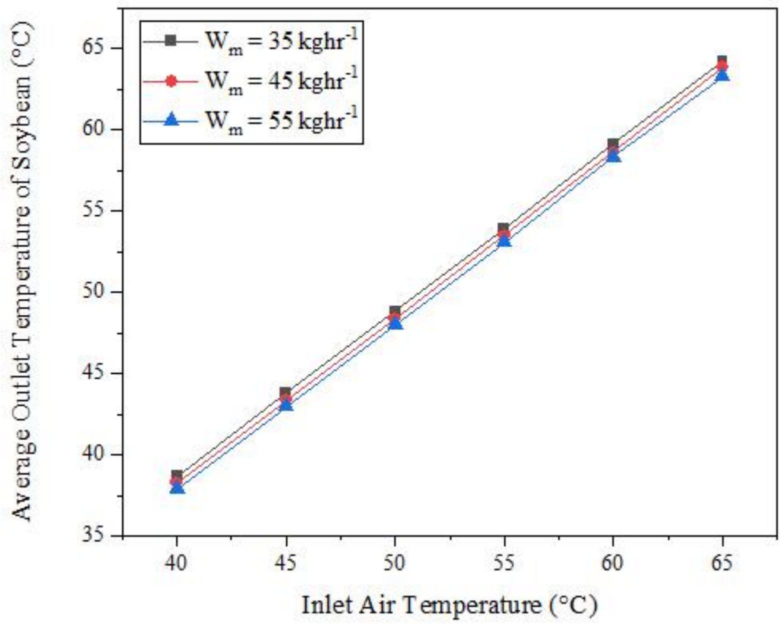

Figure 4.5 Variation of avg. outlet temperature of soybean versus temperature of inlet air at three different flow rates

Figure 4.5 shows that the variation between average outlet temperature of soybean and inlet air temperature. Three different mass flow rates of soybean samples were experimentally studied into the fluidized bed dryer and the behavior of curve is shown. As the temperature of inlet air increase, the average outlet temperature of soybean is also increased and it follows a linear curve between temperature of inlet air and average outlet temperature of soybean.

In the Figure 4.6 two parameters of the soybean sample were studied and the relationship between these two is shown. Here it is seen that the values of soybean outlet moisture content are decreasing with the increase in fluidized bed length. At the beginning of fluidized bed length, soybean outlet moisture content is decreasing sharply. Then the curve follows gradual decrement as the increased fluidized bed length.

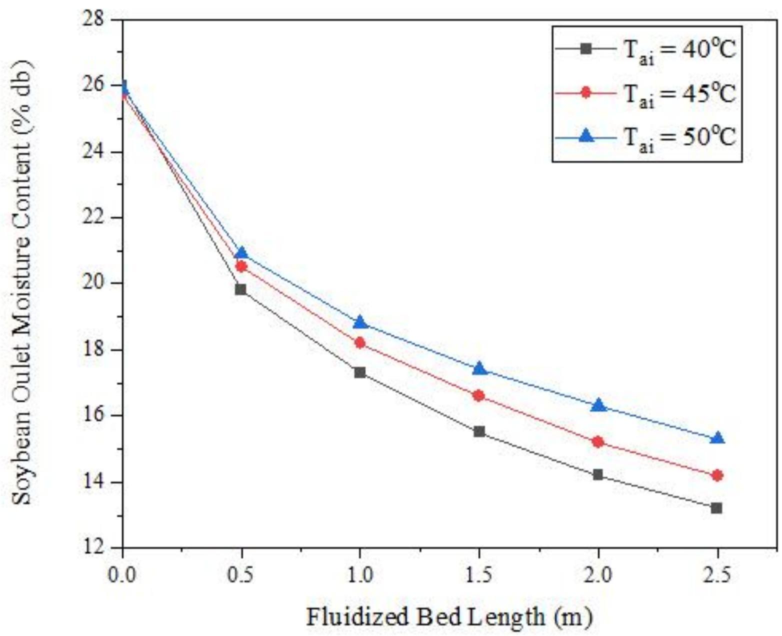

Figure 4.6 Variation of outlet moisture content of soybean versus fluidized bed length at three different inlet air temperatures

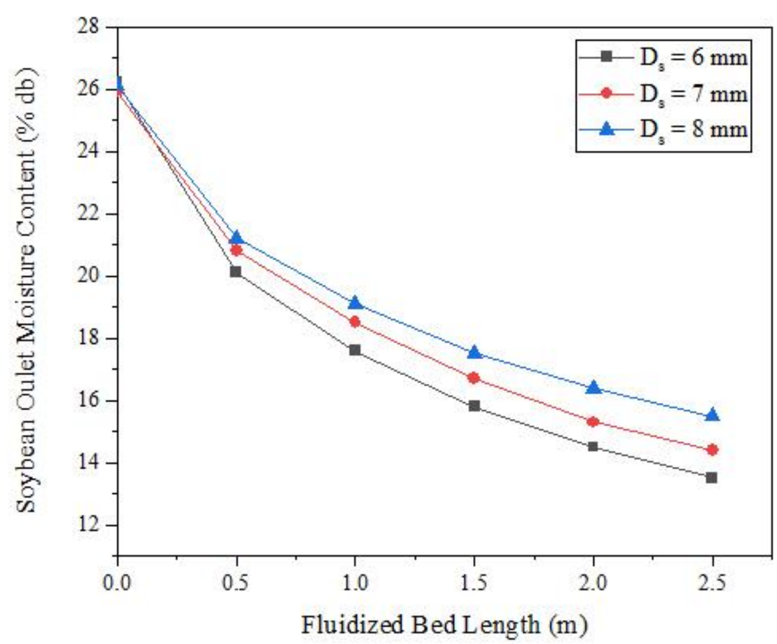

Figure 4.7 Variation of outlet moisture content of soybean versus fluidized bed length at three different diameters of soybean

Here in the Figure 4.7, it is clear that all the three curves are drastically fall in the beginning and then gradually decreasing with respect to the increase in fluidized bed length. In this graph three mass flow rates of soybean were studied and they were represented by three different color curves. As we can see in the above curve, the soybean which have greater diameter, contains more moisture content and which have lesser diameter, contains less.

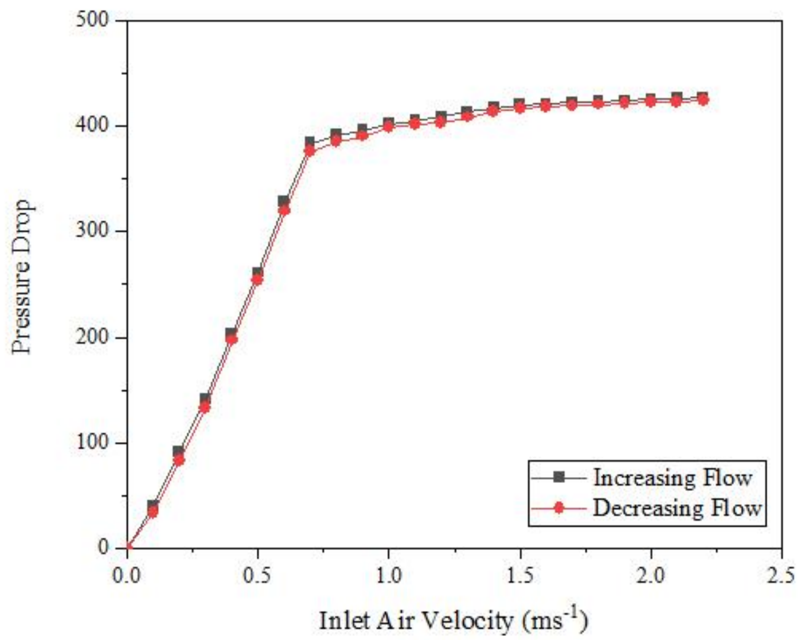

Figure 4.8 Variation of pressure drop of air versus velocity of inlet air at increasing and decreasing flow

Figure 4.8 shows the discrete points of the experimental values obtained for the pressure drop at increasing as well as decreasing air velocities. All the points of increasing flow are found slightly above in comparison of deceasing flow. For the lower velocities of inlet air, the pressure drop increases linearly and afterward it follows constant linear curve.

Conclusions

The experimental results show that during the drying of the soybean samples, the moisture content decreases first faster and then slower and finally flat or not at all inside the soybean sample. It has been shown that during the initial drying much of the moisture content is removed from the outer surface of the soybeans and slows down later. Therefore the dimensions of the fluidized bed dryer are well suited for drying the soybean sample. In the initial stage, the temperature of the soybean sample changes very rapidly but later as the drying progresses in the fluidized bed dryer, it remains almost constant. Soybean outlet moisture content versus fluidized bed length curve of the fluidized bed dryer changes very rapidly increase of the inlet air temperature that help us to understand the nature of the drying of the soybean sample. The pressure drop increases linearly when the inlet air velocity is lower and then becomes almost constant at higher inlet air velocities. The air outlet humidity increases with the increase in temperature of inlet air. Therefore we can say that as the temperature of inlet air increases, the average temperature of outlet soybean also increases linearly.

Nomenclature

d_s	Soybean diameter (mm)
U_{mf}	Minimum fluidization velocity of hot air (ms^{-1})
T_a	Air temperature (°C)
u_a	Superficial air velocity (ms^{-1})
H_{atm}	Atmospheric Humidity ($kg_{water}kg_{dry\ air}{}^{-1}$)
T_{atm}	Atmospheric temperature (°C)
Xs_i	Moisture content of inlet soybean (%)
Ta_i	Temperature of inlet air (°C)
W_m	Mass flow rate ($kghr^{-1}$)
Xs_o	Moisture content of outlet soybean (%)
Ts_o	Temperature of outlet soybean (°C)
Ta_{oavg}	Average outlet temperature of air (°C)
H_{oavg}	Average outlet humidity ($kg_{water}kg_{dry\ air}{}^{-1}$)
RH	Relative humidity (dimensionless quantity)
db	Dry basis

Greek symbols

ρ_s	Density of soybean (kgm^{-3})
ρ_a	Density of air (kgm^{-3})

Subscripts

i	Inlet
o	Outlet
s	Soybean
a	Air
atm	Atmospheric
avg	Average
mf	Minimum fluidization

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