Effect of Novel Drying Techniques on the Drying Kinetics and Physiological Quality of Soybean Seeds

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ABSTRACT

Every year one-third of the food produced worth the US $1 trillion gets spoiled during post-harvest operations. The world population is expected to be to 9.1 billion by the end of 2050 and approximately 70% extra food production is required for maintaining food security. Most of this population rise is expected to be in developing countries which are already facing an issue of food hunger and insecurity. These post-harvest losses can be broadly classified as loss due to spoilage, quality loss, seed viability loss, and nutritional loss. In developing countries, most of the losses occur due to lack of adequate knowledge and technology. However, in developed nations, the majority of the food losses have been observed at the end of the supply chain where food is discarded due to spoilage or expiry date.

A part of the harvested crop is stored as a food reserve and the remaining part is stored for next year seeding purpose. Before storage, the moisture content of the grain should be under the acceptable limit (<13%) to preserve it for a longer time and maintaining good viability. Soybean production has increased from 1991 to 2016 with USA and Brazil being at the top in production. Drying is already an energy extensive process in the industry and the case of seed grade grain drying, the energy requirement is even higher because of the low drying rate requirement employed worldwide. Microwave drying has evolved in the last two decades and the application of it can be seen in many food industries. However, in the seed industry, the application of novel techniques is not that popular, and the literature doesn't report sufficient studies on it.

In this study, microwave assisted air drying, fluidized drying and microwave assisted fluidized bed of soybean seeds was carried out at the laboratory scale and the viability, vigor and the seed coat quality was studied post drying. In microwave assisted air drying, thin layer drying at an air temperature (30, 40 and 50°C) and microwave power density (0, 0.5 and 1 W/g) was carried out using face-centered response surface methodology. A 0 W/g microwave power density was studied to highlight the comparison between air and microwave drying. The results showed that drying kinetics was improved by the incorporation of the microwaves with an increase in drying rate, shown by drying rate constant and moisture diffusivity. Also, the drying time was significantly reduced during microwave assisted air drying. However, the viability and the vigor of the seeds were damaged during microwave assisted air drying. The cracking percentage was low, but the fissure percentage was high when the microwave was incorporated. This depicts that the incorporation of microwave in the thin layer drying of soybean is not capable of producing seed grade soybean. Moreover, fluidized bed drying of soybean seeds was carried out at different air temperatures (30, 40 and 50 °C) and air velocity (1, 4 and 7 m/s) with a bed depth of 30 to 32 mm. Air velocity of 1m/s was employed to study the comparison between fixed and fluidized bed. The results showed that fluidization at low velocity improved the drying kinetics with a relatively low negative influence and an increase in air temperature had more influence on drying kinetics. The seeds dried in fluidized bed drying had germination percentage greater than 77% with a reduction in seed vigor. More than 60% of the seeds had a damaged seed coat and the seed coat hardness. In addition to this, microwaves were employed in the fluidized bed drying of soybean seeds and the drying kinetics was further improved as compared with fluidized bed drying. Also, seeds dried in microwave assisted fluidized bed drying were able to germinate with reduced vigor to the fresh seeds. In microwave fluidized bed drying almost all the seeds had damaged seed coat and the hardness of the seed coat was decreased as compared to fluidized bed drying. The fluidized bed drying technique combined with a microwave can solve the problem of non-homogeneity in bed and low drying rates in the seed drying. However, seed coat damage is a problem which requires attention in adapting these drying techniques as it could lead to spoilage and loss of viability in the seeds during storage.

RESUME

Chaque année, un tiers de la nourriture produite, d'une valeur de 1 000 milliards de dollars, est gâté pendant les opérations post-récolte. La population mondiale devrait atteindre 9,1 milliards d'habitants d'ici à la fin de 2050. Il faut environ 70% de production supplémentaire pour maintenir la sécurité alimentaire. La majeure partie de cette augmentation de population devrait se produire dans les pays en développement, qui sont déjà confrontés à un problème de faim et d'insécurité alimentaires. Ces pertes après récolte peuvent être globalement classées parmi les pertes dues à la détérioration, à la perte de qualité, à la perte de viabilité des semences et à la perte nutritionnelle. Dans les pays en développement, la plupart des pertes sont dues à un manque de connaissances et de technologies adéquates. De l'autre côté, les pays développés enregistrent d'importantes pertes de produits alimentaires à la fin de la chaîne d'approvisionnement lorsque les produits alimentaires sont jetés à la suite d'une détérioration ou d'une expiration.

Une partie de la récolte récoltée est stockée en tant que réserve alimentaire et l'autre partie est stockée pour l'ensemencement de l'année suivante. Avant le stockage, la teneur en humidité du grain devrait être inférieure à la limite acceptable (<13%) afin de le conserver plus longtemps et de maintenir une bonne viabilité. La production de soja a augmenté de 1991 à 2016, les États-Unis et le Brésil se situant au sommet de la production. Le séchage est déjà un processus énergivore dans l’industrie et dans le cas du séchage du grain de qualité graine, le besoin en énergie est élevé en raison de la méthode de séchage à faible taux utilisée dans le monde entier. Le séchage par micro-ondes a évolué au cours des deux dernières décennies et son application peut être constatée dans de nombreuses industries alimentaires. Cependant, dans l’industrie des semences, l’application de nouvelles techniques est faible et la littérature ne mentionne pas suffisamment d’études à ce sujet.

Dans cette étude, le séchage à l'air assisté par micro-ondes, le séchage fluidisé et le lit fluidisé assisté par micro-ondes ont été réalisés à l'échelle du laboratoire et la viabilité, la vigueur et la qualité de l'enveloppe de la graine ont été étudiées après le séchage. Dans le séchage à l'air assisté par micro-ondes, un séchage en couche mince à une température de l'air (30, 40 et 50 ° C) et une densité de puissance du micro-ondes (0, 0,5 et 1 W / g) ont été réalisés à l'aide de la méthodologie de surface de réponse centrée sur la face. Une densité de puissance micro-ondes de 0 W / ga été étudiée pour mettre en évidence la comparaison entre le séchage à l'air et le séchage par micro-ondes. Les résultats ont montré que la cinétique de séchage était améliorée par l'incorporation des

micro-ondes avec une augmentation de la vitesse de séchage, de la vitesse de séchage constante et de la diffusivité de l'humidité. De plus, le temps de séchage était considérablement réduit pendant le séchage à l'air assisté par micro-ondes. Cependant, la viabilité et la vigueur des graines ont été endommagées lors du séchage à l'air assisté par micro-ondes. Le pourcentage de fissuration était faible, mais le pourcentage de fissure était élevé lorsque le micro-ondes était incorporé. Cela montre que l'incorporation de micro-ondes dans le séchage en couche mince du soja n'est pas capable de produire du soja de qualité graine. Dans la deuxième partie de la thèse, le séchage en lit fluidisé de graines de soja a été effectué à différentes températures de l'air (30, 40 et 50 ° C) et à une vitesse de l'air (1, 4 et 7 m / s) avec une profondeur de lit de 30 à 32 mm. Une vitesse d'air de 1 m / s a été utilisée pour étudier la comparaison entre lit fixe et lit fluidisé. Les résultats ont montré que la fluidisation à basse vitesse améliorait la cinétique de séchage avec une faible influence et qu'une augmentation de la température de l'air avait davantage d'influence sur la cinétique de séchage. Les graines séchées au séchage en lit fluidisé avaient un pourcentage de germination supérieur à 70% avec une réduction de la vigueur de la graine. Plus de 60% des graines avaient un tégument endommagé et leur dureté. Dans la partie suivante, des micro-ondes ont été utilisées pour le séchage en lit fluidisé de graines de soja et la cinétique de séchage a été améliorée par rapport au séchage en lit fluidisé. De plus, les graines séchées lors du séchage en lit fluidisé assisté par micro-ondes ont pu germer avec une vigueur réduite par rapport aux graines fraîches. Lors du séchage en lit fluidisé par micro-ondes, presque toutes les graines avaient l'enveloppe de la graine endommagée et la dureté de l'enveloppe de la graine était diminuée par rapport au séchage en lit fluidisé. La technique de séchage en lit fluidisé associée aux micro-ondes peut résoudre le problème de la non-homogénéité du lit et des faibles taux de séchage lors du séchage des semences. Cependant, les dommages sur l'enveloppe des graines sont un problème qui nécessite une attention particulière lors de ce séchage, car ils pourraient entraîner une détérioration et une perte de viabilité des graines pendant le stockage.

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THESIS FORMAT

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines: Concerning Thesis Preparation, which are as follows:

"As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript-based thesis must conform to the following:

1. Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis).

2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.

3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.
The thesis must include the following
(a) A table of contents;
(b) An abstract in English and French;
(c) An introduction which clearly states the rational and objectives of the research;
(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper);
(e) A final conclusion and summary;

4. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g., in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

5. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the co-authored papers"

CONTRIBUTION OF AUTHORS

Chapter 1 of this manuscript contain literature review of microwave applications and microwave drying respectively. Other chapters include experimental investigations carried out in the thesis.

The following are the manuscripts prepared for publication:

1. Ayushi Anand, Vijaya Raghavan, "Hybrid microwave drying techniques for drying of food products: A comprehensive review". (Submitted to Food Engineering Reviews)

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The work here is conducted by Ayushi Anand under the supervision of Dr. G.S Vijaya Raghavan of the Department of Bioresource Engineering, Macdonald campus of McGill University, Montreal. Yvan Gareipy has provided his help and technical assistance in conducting the experiment and reviewing the manuscripts. The entire research work was carried out at the Post Harvest Technology Laboratory and Machine shop of Macdonald Campus of McGill University.

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Chapter 1 Introduction

Since prehistoric times, storing of seeds for the preservation of planting stocks from one season to another is being carried out by humans (M. Barrozo, Mujumdar, & Freire, 2014). Over the years, seed science has been developed as a sub-discipline of crop science and the endeavor of various seed scientists has led to the development of different seed quality test that are currently followed by seed industry (TeKrony, 2006). It is also assumed that food insecurity has a direct link with seed insecurity and the food crisis happen because a high fraction of produced crop gets spoiled before it even makes to the market. Seed quality often gets affected during harvest and post-harvest handling steps because of the various processing methods. These methods include grading, cleaning, drying, transportation and storage for longer use. Drying of seed is benign because the grain contains a small dormant plant which is waiting for a chance to germinate under favorable conditions. At an industrial scale, low drying rate dryers are mostly employed because of the desirable end quality of the seeds. In this study, post-harvest drying of soybean seeds and its effect on the quality of seeds has been studied. According to United States Department of Agriculture, world soybean production is 346.02 million metric tons in 2017/2018 and it is a great source of protein as well as oil. The main reason behind conducting this study is to provide literature on drying of soybean seeds with higher drying rate dryers such as microwave and various combination/ hybrid dryer.

In seed industry, fixed and moving beds are employed for the post-harvest drying of soybeans which are convective and energy extensive (M. A. S. Barrozo, Murata, & Costa, 1998; Felipe & Barrozo, 2003). However, over the past few years, several researchers have employed novel drying techniques in drying of various seeds such as rapeseeds (Łupińska, Kozioł, Araszkiewicz, & Łupiński, 2009), corn (Nair, Li, Gariepy, & Raghavan, 2011), soybean (Shivhare, Raghavan, Bosisio, & Giroux, 1993), cottonseed (Wesley, Lyons, Garner, & Garner, 1974) and wheat (Reddy, Raghavan, Kushalappa, & Paulitz, 1998). All these research conclude that appropriate selection of input process parameters can lead to significant energy savings while maintaining seed quality.

1.1 Hypothesis and implications

Microwave technology is a well-established research field in food industries and microwave drying combined with other conventional methods has proven to be energy efficient while maintaining good product quality. However, the application of microwave technology in soybean seed grade grain drying is limited. Hence, in this study, the effect of microwave assisted air drying and microwave assisted fluidized bed drying has been studied. For the comparison between conventional and novel drying methods, these techniques were compared with their conventional counterparts i.e. air drying, fixed bed and fluidized bed drying. Moreover, various seed quality parameters such as germination percentage, cracking and fissure percentage, vigor index and the seed coat hardness along with drying kinetics were studied after drying step.

1.2 Objectives

1.2.1 Overall Objectives

The overall objective of the study is to evaluate the effect of microwave drying effect on the soybean seeds and to find the effect of drying treatments on its quality.

1.2.2 Specific Objectives

1) To investigate the effect of microwave power density and air temperature on drying kinetics and quality of soybean seeds and to optimize the process to predict favorable conditions for drying.

I. Drying kinetics include prediction of drying time, modelling of the experimental data and calculation of effective moisture diffusivity and drying rate constants.
II. Quality parameters include studying germination, fissure, cracking and vigor of seeds.

2) To investigate the effect of air velocity, air temperature and microwave power on the drying kinetics and quality of seeds in fluidized and microwave assisted fluidized bed drying of seeds.

I. Drying kinetics include prediction of drying time, modelling of the experimental data and calculation of effective moisture diffusivity and drying rate constants.
II. Quality parameters include studying germination, fissure, cracking, vigor of seeds and hardness of seed coat.

Chapter II Hybrid Microwave Drying Techniques for Drying of Food Products - A Comprehensive Review

2.1 Abstract

Microwave technology is used in food industries since decades for various industrial applications such as drying, pasteurization, sterilization, cooking and extraction. In recent years, there has been a surge in techniques involving microwaves at industrial level due to its numerous advantages such as volumetric heating, great penetration depth and energy saving. This review paper discusses in great detail microwave drying including dielectric properties and heating mechanism involved in the technology. In addition to this, mathematical modelling that serves as a great medium to predict drying conditions and energy consumption have been brought to focus. Various microwave drying hybrid techniques assisted with conventional methods has been summarized and an emphasis on different approaches to reduce non-uniformity during drying have been outlined.

Keywords: Microwave drying, hybrid techniques, dielectric, drying kinetics, non-uniformity

2.2 Introduction

Microwaves are the electromagnetic waves whose frequency lie amidst 300 MHz to 300 GHz (Chandrasekaran, Ramanathan, & Basak, 2013). They are used for the telecommunication as well as for the industrial, scientific and medical purposes. To cease the conflict between these two uses, federal communications commission (FCC) accorded three frequencies; 915 MHz which is used in the industries, 2450 MHz which is preferably used for domestic as well for an industrial purpose (Menéndez et al., 2010) and 5800 MHz (Metaxas & Meredith, 1983). The dielectric properties of the food material are responsible for the conversion of microwave energy to heat energy (Curet, Rouaud, & Boillereaux, 2014; Franco, Yamamoto, Tadini, & Gut, 2015; Guo, Sun, Cheng, & Han, 2017). Heating of material with the help of microwaves has become ubiquitous in recent years and has broad applications such as drying, pasteurization, tempering, baking and sterilization in food processing industries (Chandrasekaran et al., 2013; Gupta & Leong, 2008; Metaxas & Meredith, 1983). The reason associated with the popularity of microwave heating is decrement of cooking time, high heating rates, ease of operation and less maintenance required (Salazar-González, San Martín-González, López-Malo, & Sosa-Morales, 2012).

Over the decades, drying has been used by the food industry as the most efficient method for food preservation derived from the low water activity associated with it. Foods essentially fruits, grains, vegetables and spices are dried to get their moisture level to acceptable limits (Moses, Norton, Alagusundaram, & Tiwari, 2014; Valérie Orsat, Changrue, & Raghavan, 2006). A market survey concluded that there is an increment of 3.3% in world dried food market between 2001-2006 (Atuonwu, Jin, van Straten, van Deventer Antonius, & Van Boxtel, 2011). Conventional drying methods such as air drying, vacuum drying, fluidized bed drying imply conductive and convective heat transfer approaches which often lead to the substandard quality of the end product (Maisnam, Rasane, Dey, Kaur, & Sarma, 2017). Microwave drying use electromagnetic waves that permeate through a material and cause uniform heating as compared to conventional methods (Alibas, 2009; Rattanadecho & Makul, 2016). There are few disadvantages associated with the microwave drying such as non-uniform heating, less penetration depth in deep beds and puffing (M. Zhang, Jiang, & Lim, 2010; M. Zhang, Tang, Mujumdar, & Wang, 2006). Microwave drying combined with the conventional drying techniques have proven to achieve better quality than either of microwave drying or conventional drying separately (Mahendran, 2016; Pu & Sun, 2017; Salim, Salina, Gariépy, & Raghavan, 2017). Apart from this, the frequency of the microwave used also have a significant effect on drying. It has been observed that the penetration depth is inversely proportional and loss factor is directly proportional to the frequency used (Herve, Tang, Luedecke, & Feng, 1998).

Several authors have presented a review of various aspects of microwave drying. Some of them are review on drying of fruits and vegetable related to microwave hybrid technologies (M. Zhang et al., 2006), an overview of microwave processing applications in food industries (Chandrasekaran et al., 2013), a summary of various high quality drying methods for fruit and vegetables (M. Zhang et al., 2017) and a discussion on the novel drying techniques adopted by food industries (Moses et al., 2014). Apart from these, several solutions to non-uniformity during microwave drying was reviewed by Vadivambal and Jayas (2010). Trends on microwave assisted freeze drying of fruits and vegetables were presented by Fan, Zhang, and Mujumdar (2018) and C Kumar and Karim (2017) performed a comprehensive review on microwave assisted convective drying with stress on mathematical modelling and experimental process. The primary objective of this review paper was (1) To summarize the concepts related to microwave drying research field and (2) To list all the recent developments and trends on various microwave drying hybrid technologies.

2.3 Dielectric properties of food material

Dielectric properties of the food material convey a stable correlation between the electromagnetic waves and the food material. In microwave drying, these are useful for the designing of the microwave system (Sharma & Prasad, 2002).

The combination of the two autonomous properties define the dielectric property of the material. First is the complex electric permittivity (ε^*) and the other one is the complex magnetic permeability (μ^*). Nonetheless, the dielectric properties only include complex electrical permittivity because most of the organic materials are not magnetic by nature. Therefore, a permeability of the material is close to permeability of air (Ratanadecho, 2002; Rattanadecho & Makul, 2016). Complex relative electric permittivity is illustrated by the following Eq. (1)

$$\varepsilon_r = \varepsilon_r' - j\ \varepsilon_r'' \quad \text{……(1)}$$

In the above equation, ε' is called the dielectric constant which infer the potential of the material to store energy in the presence of an electric field, whereas ε'' is called the loss factor which shows how much electric energy will be dissipated as heat (Barbosa-Canovas, Juliano, & Peleg, 2006; Içier & Baysal, 2004; Öztürk, Şakıyan, & Özlem Alifakı, 2017). The thermal energy transferred to the food material is directly associated with the loss factor. Dielectric loss result from the dipole, ionic, electronic and Maxwell Wagner responses, but at the microwave frequencies, ionic conduction and dipole rotation are the prevailing one's (Metaxas & Meredith, 1983; Ryynänen, 1995; Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010).

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_o\,\omega} \qquad \ldots\ldots(2)$$

In the above equation, d and σ represent the dipolar rotation and the ionic conduction, ε_o is the absolute permittivity of air ($8.854*10^{-12}$ F m^{-1}) and ω is the angular frequency of waves (rad s^{-1}) and σ is the ionic conductivity (S m^{-1}).

Dielectric properties are also used to determine the penetration depths of the electromagnetic waves inside the food sample. Penetration depth is the distance inside the food sample where the microwave or RF power has been reduced to 37% of the transmitted value (Kwak, Robinson, Bismarck, & Wise, 2015). The following equation represent the relation between the penetration depth and dielectric properties.

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+(\varepsilon''/\varepsilon')^2}\right]-1}} \qquad \ldots\ldots(3)$$

The penetration depth of the electromagnetic waves decreases with an increase in microwave frequency, temperature and moisture content. The principal factors affecting the dielectric properties of the material are the concentration of the material, temperature and the microwave frequency. Ling, Guo, Hou, Li, and Wang (2015) used the coaxial probe method to study the effects of frequency, temperature, moisture content and the salt content on the dielectric properties of the pistachio kernels. The result showed that regardless of the temperature and moisture content, both dielectric constant and the loss factor decreased with an increase in frequency. Further, at a particular frequency, dielectric constant and loss factor displayed increment with an increase in moisture content and temperature. Salt content did not show convincing results at the individual frequency and temperature. In a similar fashion data of Yunyang Wang, Zhang, Gao, Tang, and Wang (2013) for macadamia nut kernels confirmed the general behavior. However, the relationship between the temperature and the dielectric properties is quite varied. Boreddy and Subbiah (2016) and Ozturk, Kong, Trabelsi, and Singh (2016) showed that the dielectric properties of the egg white powder and the vegetable powder increase with the increase in temperature. However, Zhu, Guo, Jia, and Kang (2015) concluded that the dielectric constant decrease and the loss factor increase with the rise in the temperature for raw milk. A similar trend is shown for mashed potatoes and whey protein gels (J. Chen et al., 2013), at 2450 MHz as shown in figure 2.1; it is clear that the dielectric constant and the loss factor showed an increment from temperature -20 to 0 °C but from 0 to 100 °C dielectric constant linearly decrease and the loss factor first decreased slightly and then gradually increased.

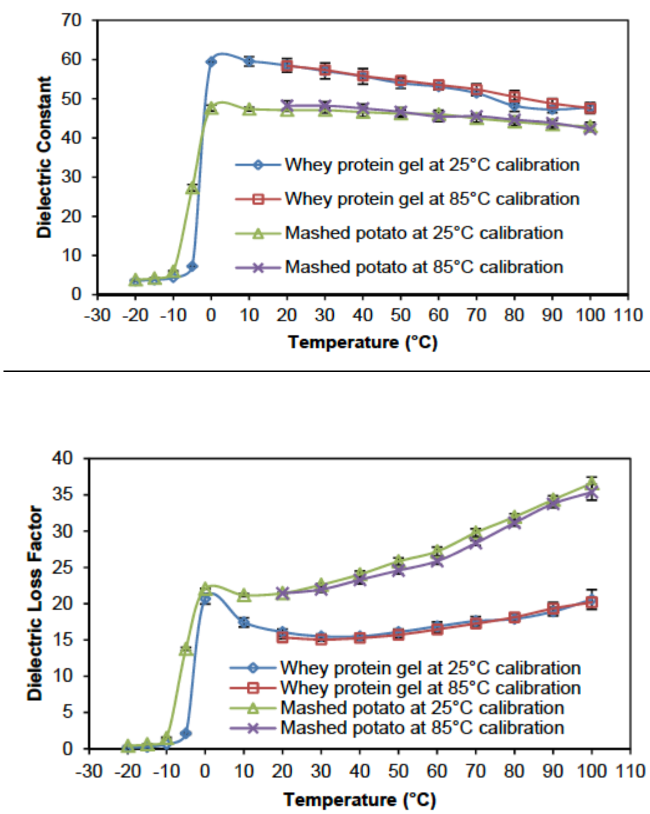


Figure 2.1 Dielectric constant and loss factor of whey protein gel and mashed potato as a function of temperature; From J. Chen et al. (2013). Used with permission.

2.4 Microwave heating and drying mechanism

Microwave heating is entirely based on the principle of conversion of varying electromagnetic energy into the heat energy defined by the volumetric heating (Mullin, 1995; Vadivambal & Jayas, 2010). Microwave heating is generally caused by the ionic and dipolar mechanisms. Dielectric heating is caused by water, a major component of food material which is dipolar. When the oscillating microwaves strike on the water molecules, the dipolar molecules starts vibrating and rotating by virtue of the continually varying electromagnetic field, and results in vibrations that take place billion times in a second and result in heating due to internal friction (Chandrasekaran et al., 2013).

The heating caused by the microwaves has been modelled by various researchers using Maxwell's equations (Ayappa, Davis, Crapiste, Davis, & Gordon, 1991; Oliveira & Franca, 2002; Vadivambal & Jayas, 2010) or Lambert's law (Campanone & Zaritzky, 2005; Vadivambal & Jayas, 2010). The propagation of the alternating electromagnetic fields in the microwave cavity is governed by Maxwell's equation and the solution for the Maxwell equation can be obtained with the help of various numerical methods. According to Maxwell's, the equations for the constant permeability and the permittivity can be given as (Geedipalli, Rakesh, & Datta, 2007; Vadivambal & Jayas, 2010)

$$\nabla \times \mathrm{E} = -\mathrm{j}\omega\mu\varepsilon\varepsilon_o \mathrm{H} \quad \text{......(4)}$$

$$\nabla \times \mathrm{H} = -\mathrm{j}\omega\mu\varepsilon\varepsilon_o E \quad \text{......(5)}$$

$$\nabla . \mathrm{E} = 0 \quad \text{......(6)}$$

$$\nabla . \mathrm{H} = 0 \quad \text{......(7)}$$

Where E is the electric field intensity (V/m), H is the magnetic field intensity (A m^{-1}), ω is the angular frequency (rad s^{-1}), μ is the permeability of free space (H m^{-1}), ε is the complex relative permittivity and ε_o is the permittivity of free space (F m^{-1}). The solution for the above equations can be obtained by various numerical methods and boundary conditions.

It is known that there is an exponential decrease in the microwave power as the waves penetrate inside the food sample (Barringer, Davis, Gordon, AYAPPA, & Davis, 1995). Since all the reflections are neglected in this case and asuuming it only fits for semi-infinite sample, modifications to the Maxwell equation leads to the evaluation of Lamberts law as follows (A. K. Datta, 1990; Vadivambal & Jayas, 2010).

$$Q_L = Q_o\, e^{\frac{-2l}{d}} \qquad \text{……(8)}$$

Where Q_L is the microwave power, Q_o is the transmitted power flux, l is the sample length (cm) and d is the penetration depth of microwaves (cm).

Microwave drying involves two simultaneous processes: water evaporation (J. R. Arballo, Campañone, & Mascheroni, 2010; Guo et al., 2017) and the drying consisting of the three stages ,i.e. heating, constant rate period followed by falling rate period (Bal, Kar, Satya, & Naik, 2010; Guo et al., 2017). During the heating period, the temperature of the product increases due to the conversion of microwave energy into thermal energy which further leads to an increase in vapor pressure of moisture. When vapor pressure becomes more than the surroundings, moisture loss takes place but at prolonged rates. In constant rate period, thermal energy is used for the vaporization of moisture from the food products. In the falling rate period, moisture content is reduced to a certain point, which leads to a situation where thermal energy converted from the microwave energy is not used for vaporization. Even though moisture loss is not much, the temperature of the product keeps rising, which further leads to overheating or charring of the food product (M. Zhang et al., 2006). Usually in microwave drying a falling rate period is not observed, or it occurs only over a small period of time. As this phenomenon is responsible for skin hardening in conventional drying, its absence in microwave drying leads to better quality products after drying. Most of the moisture diffusion occur during the constant and the small falling rate period along with other processes such as condensation or vaporization. The moisture diffusion coefficient depends on the composition, moisture content, temperature and porosity of the material (Guo et al., 2017).

2.5 Mathematical modelling of drying

Modelling of the experimental drying data is crucial in predicting the drying behavior and drying time of numerous products. In most cases, it helps in the designing of new dryers or improving the existing ones. Apart from this, mathematical modelling aid in reducing the time and cost of various scientific experiments (Simal, Femenia, Garau, & Rossello, 2005; Torki-Harchegani, Ghanbarian, Pirbalouti, & Sadeghi, 2016).

2.5.1 Empirical models

Various drying mathematical models that can be used to characterize an experimental drying data are shown in Table 3.1. MR represents the dimensionless moisture ratio and is represented as:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad \ldots\ldots(9)$$

Where, M_t is the moisture content at any time (dry basis), M_e is the equilibrium moisture content, dry basis and M_o is the initial moisture content, dry basis (Sadi & Meziane, 2015). Usually, the value of M_e is less when compared to M_t for longer drying times and can be considered zero (Akgun & Doymaz, 2005; Sadi & Meziane, 2015). Fitting of various models as shown in Table

2.1 is carried out with the help of non-linear regression (Mrittika Bhattacharya, Srivastav, & Mishra, 2015). The quality of the fitted model is determined with the help of R^2, Chi-square (χ^2) and RMSE (root mean square error) values. The higher the R^2 value and lower the χ^2 and RMSE value, better will be the fitted model representing the experimental condition (Doymaz, 2004; Ertekin & Yaldiz, 2004; Sadi & Meziane, 2015). In a research carried out by Olanipekun, Tunde-Akintunde, Oyelade, Adebisi, and Adenaya (2015), the drying of pineapple was carried out in the microwave dryer, convective dryer and under sun. After the experiments, the resulted data was fitted to nine different mathematical models. On the basis of R^2, χ^2 and RMSE values, parabolic and page models were considered best for the drying techniques stated above. The same genre of research was carried out by Horuz, Bozkurt, Karataş, and Maskan (2018) in microwave assisted air drying of apple. Several mathematical models were fitted, and the best fitted model was the modified logistic model. Model fitting usually involves fitting the experimental data to the number of models previously used and then finding the best one on the basis of various factors like R^2. The type of model that explain drying behavior depend on the drying conditions and the type of product used. However, empirical models do not consider the change of moisture and temperature as a function of space and time. Hence, this type of modelling has not found much application at an industrial scale where scenarios and operating conditions change (Ah-Hen, Zambra, Aguëro, Vega-Gálvez, & Lemus-Mondaca, 2013; A. Mujumdar & Huang, 2007; Sabarez, 2015).

Table 2.1 Various mathematical model used by researchers for modelling drying data (Rafiee et al., 2009; Ranjbaran & Zare, 2012)

Model Name	Model equation
Page	$MR= \exp(-k(t)^n)$
Lewis	$MR= \exp(-kt)$
Henderson and Pabis	$MR= a \exp(-kt)$

Logarithmic	MR= a exp(-kt) + c
Wang and Sing	$1 + at + bt^2$
Two term exponential	MR= a exp(-kt) + (1-a) exp(-kat)
Diffusion Approach	MR= a exp(-kt) + (1-a) exp(-kbt)
Verma *et al.*	MR= a $\exp(-k_1t)$ + (1-a) $\exp(-k_2t)$
Two term	MR= a $\exp(-k_1t)$ + b $\exp(-k_2t)$
Midilli *et al.*	MR= a $\exp(-k(t)^n)$ + bt
Modified Henderson and Pabis	MR= a $\exp(-k_1t)$ + b $\exp(-k_2t)$ + c $\exp(-k_3t)$

2.5.2 Diffusion theory and effective moisture diffusivity

Researchers use several mechanisms to understand the concept of moisture transport during drying, but the most prevailing one is the effective moisture diffusivity (Das & Arora, 2017). The assumptions considered are: the moisture content is uniform and the removal is entirely due to diffusion, moisture diffusivity is constant with no shrinkage and surface mass transfer resistance is negligible. The concentration gradient and pressure gradient are served as a driving force for the migration of liquid and water vapor respectively. Fick's second law of diffusion, which is used to explain moisture transport is stated as:

$$\frac{\partial M}{\partial t} = D_{eff}\ \nabla^2 M \qquad \text{……(10)}$$

Where M is the moisture content and D_{eff} is the effective moisture diffusivity in $m^2\ s^{-1}$ (Dadalı, Apar, & Özbek, 2007).

The solutions for the above equation for various shapes of the material was calculated by Crank (1979) and are listed in Table 2.2. The method of the slope is generally used to find the effective moisture diffusivity from the equations proposed in Table 2.2. Dadalı et al. (2007) have used this method to find out the effective moisture diffusivity in microwave drying of okra. The okra shape was assumed to be a sphere and the required equation was used to calculate the diffusivity. Horuz, Bozkurt, Karataş, and Maskan (2017) also calculated the diffusivity value during microwave convective drying of apricot halves where the shape of apricot was assumed to be an infinite slab. In their study, Sadi and Meziane (2015) studied the microwave drying of olive pomace where the shape of the drying product was assumed to be a cylinder and the required equation was used to calculate the moisture diffusivity.

Table 2.2 Values of effective moisture diffusivity for various shapes proposed by Crank (1979)

Shape	**Solution**
Slab	$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 . D_{eff} . \Pi^2}{L^2} . t\right)$
Cylinder	$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left(-\frac{\lambda_n^2 D t}{r^2}\right)$
Sphere	$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} = \frac{6}{\Pi^2} \exp\left(-\frac{D_{eff} \Pi^2}{r^2} . t\right)$

© MR is the moisture content, M_t is the moisture content at particular time, M_o is the initial moisture content, M_e is the equilibrium moisture content, D_{eff} is the effective moisture diffusivity ($m^2 s^{-1}$), L is the thickness of the sample (m), t is the drying time, r is the radius of cylinder or sphere (m), λ^2_n is the nth root of the bessel function of zero order

Moisture diffusivity value depend on the process variables of microwave drying, or microwave assisted drying. The dependence of moisture diffusivity on different process variables for various drying methods and products are shown in Table 2.3.

Table 2.3 Effect of various process parameter on moisture diffusivity

Product Type	Drying method	Process parameter	Effect	Reference
Garlic cloves	Microwave-convective	Air Temperature	Increase	Sharma and Prasad (2004)
		Microwave power	Increase	
		Air velocity	Increase	
Okra	Microwave drying	Microwave power	Increase	Dadalı et al. (2007)
		Sample amount	Decrease	
Pomegranate arils	Microwave vacuum drying	Microwave power	Increase	Dak and Pareek (2014)
		Sample mass	Decrease	
		Vacuum pressure	No effect	
Apple	Osmotic-microwave drying	Osmotic pre-treatment	Decrease	Prothon et al. (2001)
Button mushroom	Freeze drying	Drying temperature	Increase	Pei et al. (2014)
		Material thickness	Decrease	
		Chamber pressure	Decrease	
Eggplant	Osmotic microwave-infrared drying	Osmotic treatment	Decrease	Aydogdu, Sumnu, and Sahin (2015)
		Microwave power	Increase	
		Infrared power	Increase	
Diced apple	Microwave-spouted bed drying	Microwave power	Increase	H Feng, Tang, and Cavalieri (1999)

		Air temperature	Increase	

Activation energy and the dependence of moisture diffusivity on temperature is calculated through the Arrhenius exponential model (Dadalı et al., 2007; N. Jiang et al., 2016; Zarein, Samadi, & Ghobadian, 2015) stated below:

$$D_{eff} = D_{eff0} \exp\left(\frac{-E_a m}{P}\right) \qquad \text{......(11)}$$

Where D_{effo} is the pre exponential factor (m^2 s^{-1}), P is the microwave power (W), E_a is the activation energy in the dryer (W g^{-1}), m is the mass of sample (g) and D_{eff} is the effective moisture diffusivity. Logarithmic transformation of the above equation is used to calculate the activation energy:

$$\ln D_{eff} = \ln D_{eff0} - \left(\frac{E_a m}{P}\right) \qquad \text{......(12)}$$

Nevertheless, this method has a drawback because shrinkage of product and the change in moisture diffusivity is neglected. Golestani, Raisi, and Aroujalian (2013) did mathematical modelling of convective drying of apples by taking shrinkage and change in diffusivity along with temperature and moisture into consideration. Three models i.e. constant moisture diffusivity without shrinkage, constant moisture diffusivity with shrinkage and variable moisture diffusivity with shrinkage were studied for their validity. The results showed that the model including variable moisture diffusivity with shrinkage was found best for the experimental data.

2.5.3 Heat and mass transfer models

During drying, heat is generated throughout the sample and moisture transfer from the food sample takes place. Therefore, a more extensive type of modelling approach which include the laws of conservation of heat and mass is often required. Numerous studies on heat and mass transfer modelling in microwave drying field is listed in Table 2.4.

Hao Feng, Yin, and Tang (2012) have presented the full comprehensive review of the modelling techniques and different types of models available, including empirical, diffusion and various heat and mass transfer models. Various emerging computational methods like computational fluid dynamics required for the modelling of the drying process is reviewed by Defraeye (2014). However, these methods explained, only work for drying process where a drying material is the main focus, not in the case where process design or cost calculations etc. is required.

The mathematical modelling is essential for design and optimizing of the drying process. An in-depth knowledge of modelling considering all scenarios during an operation is required in the case of heat and mass transfer modelling for accurate predictions.

Table 2.4 Studies incorporating heat and mass transfer models for the modelling of the drying process

Product type	Drying method	Model Description	Results	References
Food material (not specified)	Intermittent microwave-convective drying	Multiphase model using Maxwell equations for microwave heat generation.	The intermittent microwave achieved more uniformity and model predicted the standard wave pattern inside the cavity.	Chandan Kumar, Saha, Sauret, Karim, and Gu (2016)
Apple	Intermittent microwave-convective drying	Diffusion based single phase model using Lamberts Law for microwave absorption.	Model showed the good agreement with the experimental data and the moisture distribution showed that the high amount of moisture is accumulated in the center of the sample.	Chandan Kumar, Joardder, Farrell, Millar, and Karim (2016)
Wheat seeds	Microwave-convective drying	Coupled microwave model with convective drying model.	Model predicted the drying conditions well and the coupled model predicted slower drying than microwave drying model.	Mohamed Hemis, Choudhary, and Watson (2012)
Pears	Microwave-osmotic drying	Combined two diffusional osmotic model with microwave model using Lamberts Law.	Model which combined the mechanisms involving in both the drying methods was developed and a good agreement was found with the experimental values.	J. Arballo, Campanone, and Mascheroni (2012)

Soybean	Microwave-convective drying	Coupled microwave model with convective drying model.	Combined process resulted in less drying time and lower power levels should be used in soybean drying.	M Hemis and Raghavan (2014)
Canola seeds	Microwave-convective drying	Coupled microwave model with convective drying model.	Combined process resulted in higher drying rate and the result showed that reflected microwave power resulted in decrement in drying rate.	Mohamed Hemis, Choudhary, Gariépy, and Raghavan (2015)
Soybean and canola	Microwave-convective drying	Coupled distributed parameter model with microwave model for the study.	The result showed that lower microwave power density (less than 0.3 W/g) should be considered for drying of oilseeds to prevent the cracking and protein damage.	Agrawal and Methekar (2017); Mohamed Hemis, Gariépy, Choudhary, and Raghavan (2017)
Pumpkin	Convective drying	Physics based model for incorporating diffusivity as a function of temperature inside the food sample.	Drying showed two falling rate period and no constant rate drying period. Model satisfactorily fitted to the experimental conditions.	Agrawal and Methekar (2017)

2.6 Energy consumption

Drying of food material requires an energy for the phase change of water into vapor and it is considered an extensive energy process due to high latent heat of vaporization of water (Sabarez, 2016). With an increasing concern over energy savings and resources, it is essential for an industrial process to be energy efficient. It is noted that drying consumes 12% of the total energy required for the manufacturing process in industries (Bahu, 1991).

Researchers all over the world have studied different drying methods and their energy consumption for various food products. Energy consumption calculations for different drying methods are listed in Table 2.5. Apart from these calculations, various scholars have employed an electric meter for the energy calculations during drying experiments (Cao, Zhang, Mujumdar, Zhong, & Wang, 2018; N. Jiang et al., 2017; Orikasa et al., 2018).

Table 2.5 Total energy calculation for various drying methods (Motevali, Minaei, Khoshtaghaza, et al., 2011)

Drying method	Calculation method	Parameters
Convective Drying	$E_t = A.v.\rho_a.C_a.\Delta T.t$	E_t is total energy (kWh), A is the area of sample container (m^2), v is air velocity ($m\ s^{-1}$), ρ_a is air density ($kg\ m^{-3}$), t is the total drying time (h), ΔT is the temperature difference (°C), Ca specific heat of air ($kJ\ kg^{-1}\ °C^{-1}$)
Microwave Drying	$E_t = G.t$	G is the microwave power (kW), t is the drying time (h), E_t is the total energy consumed

Vacuum Drying	$E_1 = L.t$ $E_2 = Q.I.\cos\theta.\ t_o$ $E_t = E_1 + E_2$	E_1 is the energy consumed by vacuum pump (kWh), L is the pump power (kW), t is the drying time (h), E_2 is energy consumed by heaters (kWh), Q is voltage, I is current, t_o is operating time of heaters
Infrared Drying	$E_1 = K.t$ $E_2 = \frac{V^3}{16600}$ $E_t = E_1 + E_2$	E_1 predict energy used by IR lamp, K is lamp power (kW), t is the drying time (h), E_2 is energy consumed by blower, V is the air velocity (m s^{-1}), E_t is the total energy consumed

Motevali, Minaei, Khoshtaghaza, et al. (2011) compared the energy consumption of several drying methods during drying of mushroom slices. The results showed that out of convective, microwave, infrared, convective-infrared, vacuum and convective-vacuum drying, minimum energy was consumed during microwave drying and the maximum was visible during vacuum drying. Same results were replicated by Motevali, Minaei, and Khoshtagaza (2011) for pomegranate arils. Szadzińska, Łechtańska, Kowalski, and Stasiak (2017) did the comparative analysis of energy consumption during convective drying assisted by microwave or ultrasound on green pepper. The study showed that convective assisted by microwave and convective assisted by microwave-ultrasound resulted in lower use of energy. Comparison between freeze drying and microwave assisted freeze drying regarding energy consumption was carried out by Cao et al. (2018) on barley grass, which stated that microwave assisted freeze drying resulted in lower consumption of energy. Combining osmotic dehydration with microwave assisted drying techniques also resulted in a decrease in consumption of energy during drying (Al-Harahsheh, Ala'a, & Magee, 2009; Pereira, Marsaioli Jr, & Ahrné, 2007; Piotrowski, Lenart, & Wardzyński, 2004).

2.7 Hybrid microwave drying techniques

The plethora of research work has been done in the field of microwave drying and figure 2 shows the chronological order of the number of publications for various hybrid microwave drying techniques. It is evident from figure 2.2 that since 1990 there have been a lot of work done on microwave drying and is still following an increasing trend. Following sections discuss in great detail about working and principle of these techniques with recent developments.

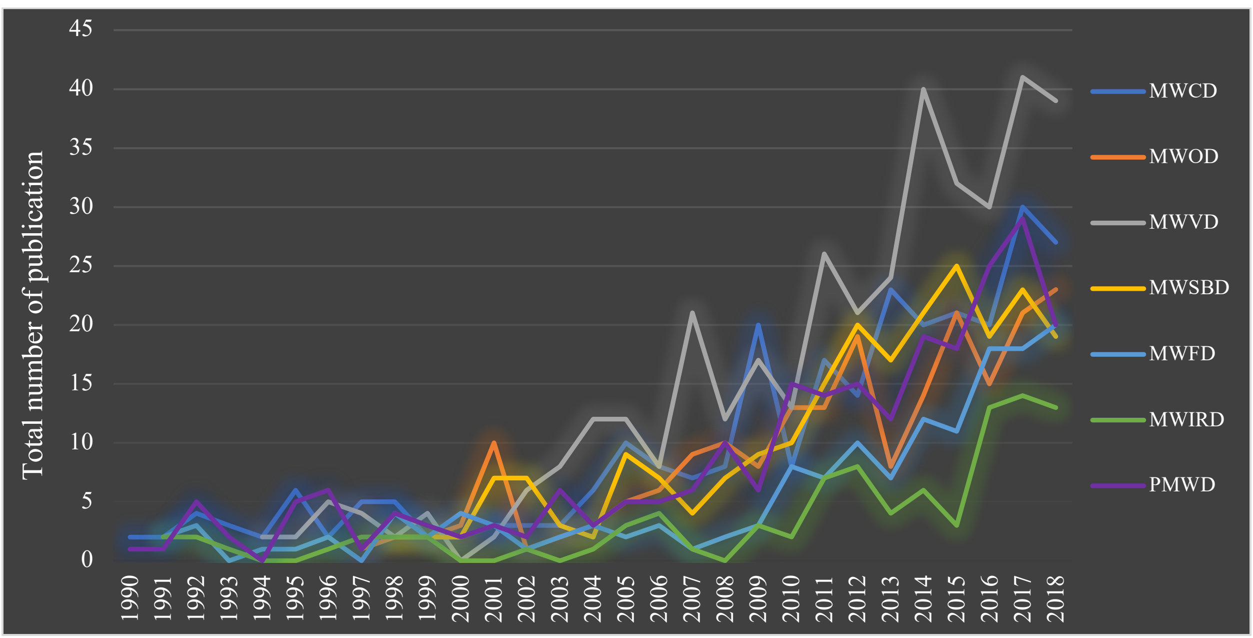


Figure 2.2 Timeline of number of publications for various microwave hybrid drying techniques (Source: Web of Science); Microwave convective drying (MWCD), Microwave assisted osmotic drying (MWOD), Microwave assisted vacuum drying (MWVD), Microwave assisted spouted bed drying (MWSBD), Microwave assisted freeze drying (MWFD), Microwave assisted infrared drying (MWIRD) and Pulsed microwave drying (PMWD).

2.7.1 Microwave assisted air drying

Convective air drying is one of the widely used drying techniques at an industrial scale because of its low cost, smooth operation, less maintenance and providing required food safety associated with water activity (Doymaz, 2004). Despite of its many advantages, there are many drawbacks associated with it such as less rehydration ratio (Khraisheh, McMinn, & Magee, 2004), high temperature required to reduce the drying time (Maskan, 2000; Mwithiga & Olwal, 2005), shrinkage (N. Wang & Brennan, 1995), change in shape, hard end product and volume loss (Alibas, 2009; Maskan, 2001; Mayor & Sereno, 2004).

It is evident that the combination of the microwaves and hot air drying help in achieving better results. Two phenomena can explain this, first microwaves cause heating of the water inside a sample, which in turn aid in the transportation of moisture from the inside of the sample to the outside and creating moisture and pressure gradients. After this, hot air is used for the vaporization of moisture on the surface of the sample. Drying time is also reduced due to the significant increment in heat transfer during the falling rate period, which is not evident during the convective drying (Gaukel, Siebert, & Erle, 2017).

Several contributions of various researchers who have employed the concept of microwave and hot air drying along with their results are shown in Table 3.6. Malekjani, Emam-Djomeh, Hashemabadi, and Askari (2018) modelled the microwave convective drying of hazelnuts and the two term and midilli et. al. models were found best fit for drying conditions. Microwave power was having more effect on drying kinetics than air temperature. Effect of pre-treatments such as ultrasound, steaming and dipping (control) on the microwave convective drying of parsley leaves was studied by Dadan et al. (2018). Various parameters like total phenolic contents, antioxidant capacity, chlorophyll (a and b) and lutein content was studied. The results showed that higher phenolic content was achieved during steaming pre-treatment at lower air temperature and microwave power. The highest retention of chlorophyll a was found during dipping at high temperature and microwave power. In the case of chlorophyll b, retention was maximum for dipping at higher microwave power and air temperature. Results of lutein content were not significant at all the parameters and antioxidant capacity was not affected by both treatments.

Table 2.6 Various results of microwave assisted convective drying of different food products

Product dried	Results	Reference
Green pepper	Decrease in drying time, better retention of vitamin C, better color and energy efficient process	(Łechtańska, Szadzińska, & Kowalski, 2015)
Olive Pomace	Drying rate increases with increase in temperature	(Gögüs & Maskan, 2001)
Carrots	Decrease in drying time and better product quality of end product	(Prabhanjan, Ramaswamy, & Raghavan, 1995)
Apple and Mushroom	Decrease in drying time and better rehydration capability of the dried product	(Funebo & Ohlsson, 1998)
Garlic cloves	Decrease in drying time with better quality of end product	(Sharma & Prasad, 2001)
Cranberries	Shortest drying time was observed for microwave assisted drying; No significant difference of colour of product in four methods; microwave improved the drying rate but have poor rehydration properties; toughness was minimum during freeze drying of product	(Beaudry, Raghavan, Ratti, & Rennie, 2004)
Pumpkin slices	Good drying period, better quality and energy efficient	(Alibas, 2007)
Macadamia nuts	Shorter drying times and was able to preserve natural quality of the nuts	(Silva, Marsaioli Jr, Maximo, Silva, & Goncalves, 2006)

2.7.2 Osmotic dehydration assisted microwave drying

Osmotic dehydration is a basic dehydration technique in which the sample is placed in a hypertonic solution mostly sugar solution for a designated period. Usually, 50% of the decrement from the initial mass is achieved, but this decrease depends on various factors such as immersion time, solution concentration and temperature. Prothon et al. (2001) studied the combination of osmotic pre-treatment and microwave drying of apple. Various quality parameters such as rehydration capacity, texture, color and microstructure were also determined. Results obtained from the study showed that osmotic dehydration changed the moisture content from 89% to 71% and treated samples reported to have less drying time and sound quality than the non-treated sample. Post-effects of microwave power and sodium chloride concentration on osmotically treated tomato pomace was studied by Al-Harahsheh et al. (2009). They concluded that an increase in a microwave power, in turn, increases the drying rate and osmotic pre-treatment also leads to an increase in drying rate. However, in the early stages of drying, the sample treated with higher concentration of sodium chloride accounts higher drying rate due to the dielectric properties of polar sodium chloride. But in the end stages, one with the highest concentration of sodium chloride results in lower drying rate since osmotic solution binds with water and make moisture loss difficult. Lagnika et al. (2018) studied the effect of various pre-treatment such as blanching, osmotic dehydration, ultrasound, ultrasound before osmotic dehydration and ultrasound assisted osmotic dehydration on microwave vacuum drying of sweet potato. The outcome indicated that pre-treatment significantly helps in reducing drying time and improving the quality of the dried product. Moisture loss was highest in the case of ultrasound pre-treatment and lowest in the case of blanching when drying time was the same for both the treatments. The highest rehydration ratio was obtained in the case of ultrasound and lowest in the case of osmotic dehydration. Regarding color, ultrasound assisted by osmotic dehydration showed a minimum color change from the fresh sample. The hardness was highest in the case of osmotic and minimum in the case of ultrasound. The dielectric constant was highest in the case of blanching and loss factor was maximum in the case of osmotic dehydration. Multi stage drying processes result in better quality of end products with better drying rates. Osmotic-steam blanching pre-treatment followed by Microwave-infrared-hot air drying was studied by Deepika and Sutar (2018). Firstly, the lemons were osmotically dried in 20% NaCl solution for 180 min at 30°C followed by steam blanching for 1 min. After this, the samples were dried in infrared hot air dryer until the moisture content reached 30% (w.b) because infrared results in heating of surface and surface moisture become abundant below 30%. In the end, the samples were dried in microwave-hot air until the moisture content reached 9% (w.b). The dried samples resulted in having a better quality with lower energy consumption due to the multi-stage drying. Also, the water activity was reduced even at higher final dried samples moisture content (9% than 6%) which means that product would be safe from spoilage even at higher moisture content.

Despite the advantages of this hybrid technique, there are certain disadvantages associated with it. While using osmotic dehydration as a pre-treatment, a considerable amount of solute combine with the product leading to alterations in its constituents and reporting higher processing time with lower drying rate (Dhingra, Singh, Patil, & Uppal, 2008; Ozkoc, Sumnu, & Sahin, 2015). Apart from that, the movement of certain constituents from drying material to the osmotic solution is also a problem during osmotic dehydration pre-treatment (Garcia-Noguera et al., 2010). To address these disadvantages, Gamboa-Santos and Campañone (2018) used the edible film (alginate lactate) coating on strawberries and studied the drying kinetics of the process. The sugar gain in the sucrose solution during osmotic pretreatment was 42% less in the case of coated strawberries. The authors have also shown the results of coating in Figure 2.3, where due to its hydrophilic properties, it did not affect the drying of strawberries. However, solids movement was significantly restricted by the application of the coating. The osmotically dehydrated sample has resulted in better drying rates and lower moisture diffusivity than the fresh ones.

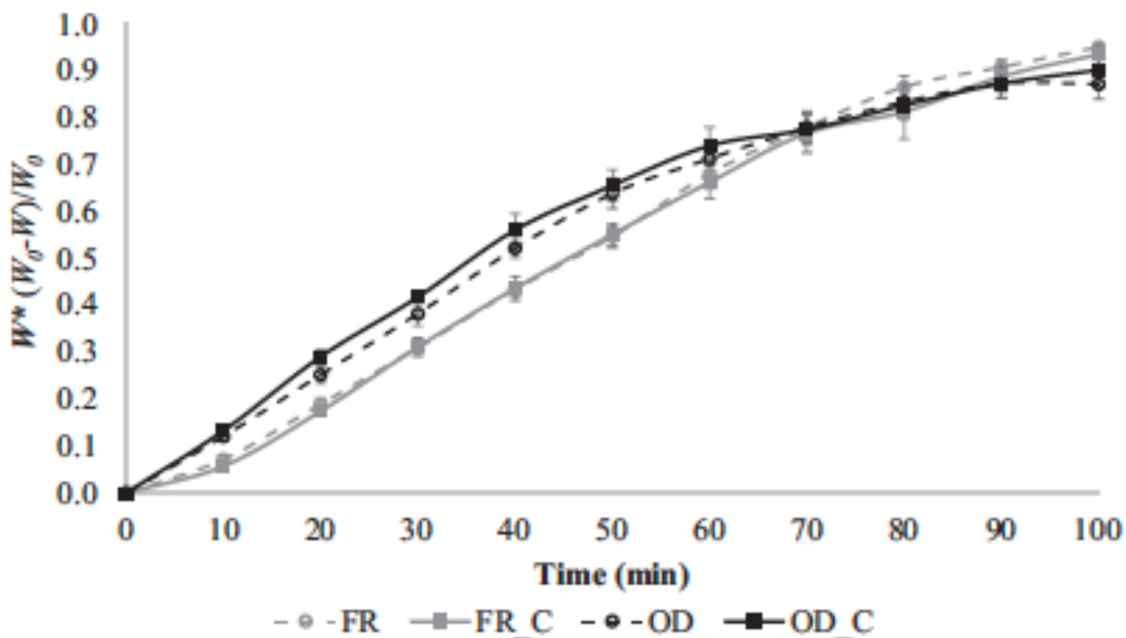


Figure 2.3 Moisture content as a function of time during drying for fresh (FR, FR_C) as well as osmotically treated (OD, OD_C) strawberries with or without coating; W* is dimensionless moisture content; W_0 is the moisture content of fresh samples; W is the moisture content at any time during drying. Reproduced from Gamboa-Santos and Campañone (2018), with permission from Taylor & Francis

2.7.3 Microwave assisted vacuum drying

In the case of vacuum drying lower pressures are used for the removal of water from the sample. Vacuum dry the samples at much lower temperature than at atmospheric pressure. In vacuum drying, there is a rapid movement of water from the interior to the exterior surface following which it gets evaporated by the energy. Moreover, vacuum drying also results in the reduction of the boiling point inside the food sample. As a result, a vapor pressure gradient is created between the center and the surface of the food sample which result in higher drying rate (M. Zhang et al., 2006). During the process, browning of food doesn't occur due to the lower oxygen partial pressure in the drying chamber. Therefore, this process is highly recommended for the products like fruits or vegetables which have a low tolerance towards heat or oxygen (Jaya & Das, 2003). The major problem with the vacuum drying is the low heat transfer rate due to absence of convective air. However, vacuum drying combined with microwaves have proven to produce superior quality end product (Giri & Prasad, 2007). But the hybrid technique is not efficient because of its high capital requirement. It is generally recommended as an alternative method for the convective drying and should be used in conditions which require high quality of dried product (Drouzas & Schubert, 1996).

In the study conducted by Calín-Sánchez et al. (2011), the effect of vacuum level and microwave power was studied during the microwave vacuum drying of rosemary. Drying kinetics of rosemary by microwave assisted vacuum drying is shown in Figure 2.4 and 2.5. A critical point K was used to separate the two drying periods, i.e. falling rate drying period and constant rate drying period. A linear function described the constant rate drying period and the Henderson-Pabis model described the falling rate drying period. A shift of vacuum levels from 72 to 74 kPa to 96-98 kPa at 360 W resulted in an increase of rate constants of both drying period and the change of microwave power from 240 W to 480 W also increased the rate constants of both drying periods. Drying time also showed a decrease when there is an increase in both vacuum levels and microwave power. Similar results of reduction in drying time are also reported by Musielak and Kieca (2014) in microwave vacuum drying of beetroot and carrot slices.

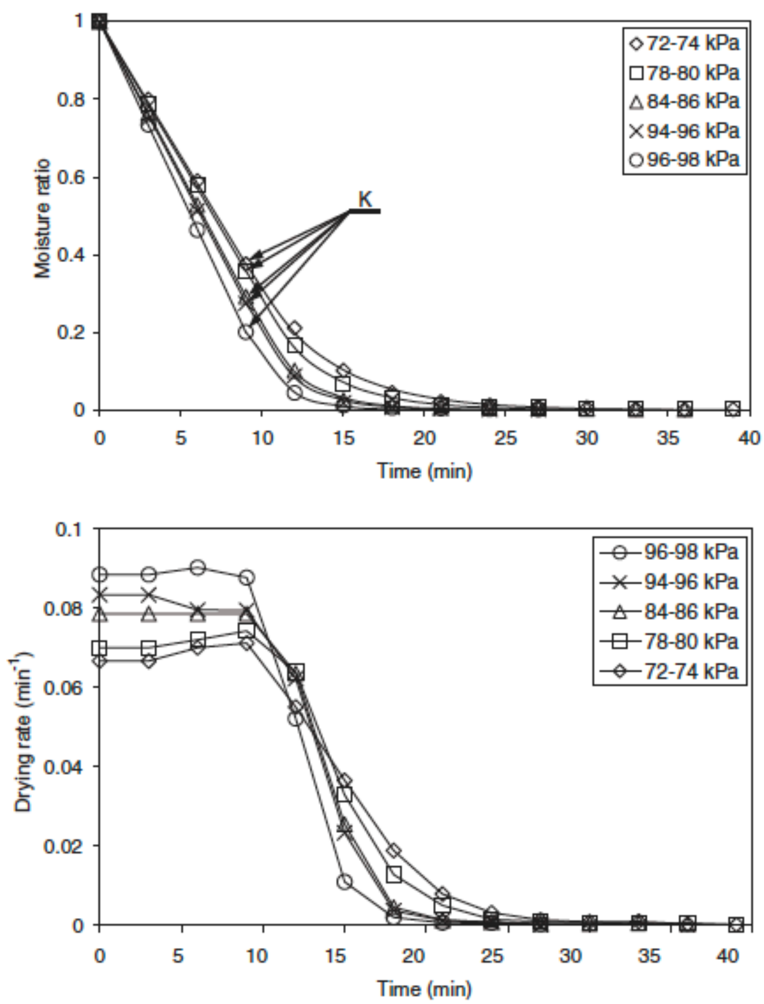


Figure 2.4 Effect of vacuum levels on drying kinetics of rosemary. Reproduced from Calín-Sánchez et al. (2011), with permission from Elsevier.

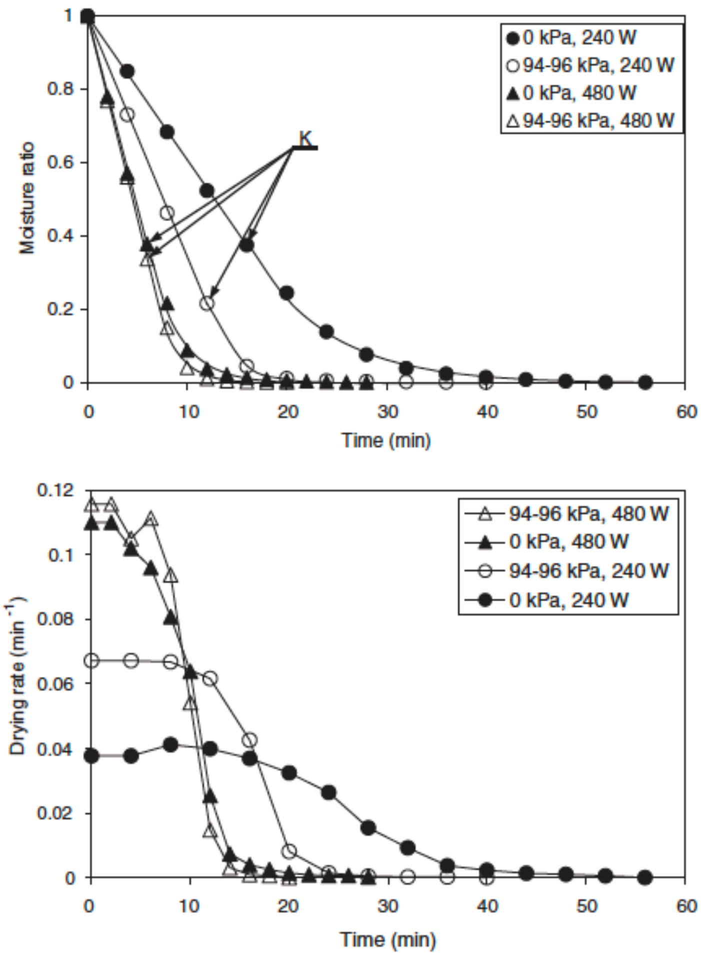


Figure 2.5 Effect of different microwave power levels at different vacuum levels on drying kinetics of rosemary. Reproduced from Calín-Sánchez et al. (2011), with permission from Elsevier.

Microwave vacuum drying work at reduced pressures which often need low temperatures for drying. As a result of these, the end products have better texture, color, good rehydration capacity and higher nutritional value. Sometimes osmotic dehydration is used as a pre-treatment in the microwave vacuum drying (Corrêa, Dev, Gariepy, & Raghavan, 2011). The advantages associated with this are energy saving (Corrêa et al., 2011; Pan, Zhao, Zhang, Chen, & Mujumdar, 2003), higher nutritional value (Corrêa et al., 2011; V Orsat, Yang, Changrue, & Raghavan, 2007) and better rehydration capacity (Changrue, Orsat, & Raghavan, 2008; Corrêa et al., 2011). Corrêa et al. (2011) studied the effect of immersion time, osmotic solution concentration and drying temperature on moisture content, rehydration capability, appearance and shrinkage in the microwave-vacuum drying of pineapple with the osmotic method as a pre-treatment. The results of the study are represented in Table 2.7.

Table 2.7 Effect of osmotic pre-treatment in the microwave-vacuum drying of pineapple

	Osmotic solution concentration	**Immersion time**	**Drying temperature**
Moisture content	No significant effect	No significant effect	Significant effect
Rehydration capacity	Significant effect	No significant effect	No significant effect
Visual quality	Significant effect	Significant effect	No significant effect
Shrinkage	Significant effect	Significant effect	Higher significant effect

Moisture diffusivity is the primary parameter in the optimization of any drying process related to food or any other material. Dak and Pareek (2014) studied effective moisture diffusivity of pomegranate arils under microwave vacuum drying. They suggested that there was an increment in the effective moisture diffusivity with either increase in microwave power or decrease in sample mass at certain levels of vacuum. Abano, Ma, and Qu (2012) also obtained similar results in the drying of tomato slices in which increase of microwave power increases effective moisture diffusivity. The results also showed that there was a decrease in brightness of tomato slices with an increase in microwave power. Microwave vacuum hybrid technique was found to be better in the drying of turmeric by Hirun, Utama-ang, and Roach (2014). The results displayed that with microwave vacuum drying technique, turmeric showed better color and the presence of a greater number of bioactive compounds in higher quantities.

2.7.4 Microwave assisted spouted bed drying

Non-uniformity of electromagnetic waves leads to various cold and hot spot in the final product which is a major concern during microwave drying. The products with high sugar content often get hot and burned partially due to non-uniform heating. This non-uniformity is generally reduced by the movement of drying sample in a drying chamber. When the product is granular or coarse, then the movement by fluidized or spouted bed have shown reduction in the non-uniformity of the electromagnetic waves inside the drying chamber (Huang, Zhang, Adhikari, & Yang, 2016). Generally, group D type of material in Geldart classification of particles is well suited for spouted bed drying as these are not suitable for standard fluidized bed dryers and most of the particulate food/agriculture products also fall in this category (H Feng et al., 1999). When the hot air is circulated through the particulate bed, an equilibrium has been achieved after a particular flow rate and the value of this flow rate is known as critical flow rate. If the flow rate is further increased, then this leads to the circular movement of particulate matter further leading to the stage of fluidization. As a result of these movements, the boundary layer at the particle surface constantly changes which lead to better heat and mass transfer rates in the drying sample, further resulting in the higher grade of the dry product (M. Zhang et al., 2006).

H Feng and Tang (1998) used the hybrid technique of microwave and spouted bed drying for diced apples. The results showed the more uniform distribution of temperature in the diced apple, which further lead to the good visual quality of diced apples after drying. The temperature distribution of ten diced apple under microwave spouted bed drying and microwave drying with stationary bed and hot air is shown in Figure 2.6 and the result showed that temperature variations during microwave spouted bed drying were small and there was more uniform heating during spouted bed drying than in a stationary bed. After studying the hybrid technique, H Feng et al. (1999)

carried out the research further to find out the effect of spouted bed air temperature and microwave power levels on drying. The results showed that the drying rate is increased by an increase in air temperature and power level, but at high microwave power level, the product showed some signs of darkening.

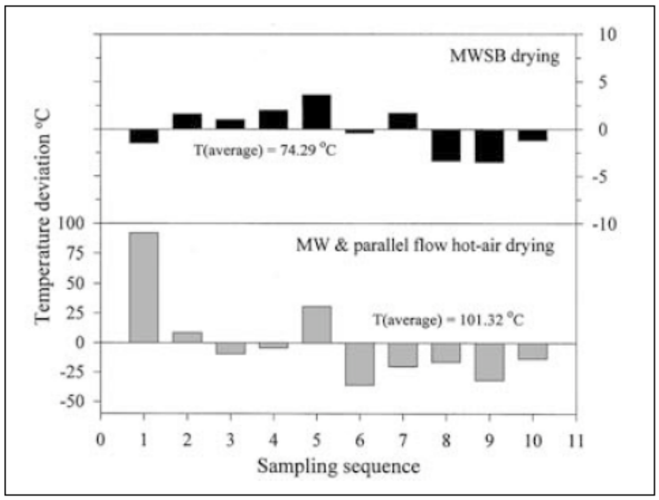


Figure 2.6 Temperature variation of 10 apple pieces taken after microwave assisted spouted bed drying and microwave assisted convective drying. Reproduced from H Feng and Tang (1998), with permission from Wiley online library.

A comparative study between spouted bed drying and microwave assisted spouted bed drying was studied by Kahyaoglu, Sahin, and Sumnu (2010) in which various physical parameters such as bulk density, bulk porosity, pore size distribution, sphericity, color, yield and water absorption capacity etc. were studied in drying of parboiled wheat. The result of the study is presented in Table 2.8. Three different modes of drying involving spouted bed and microwave drying in dehydration of potato chips were studied by Yan et al. (2010). The first method involved microwave drying in a spouted bed (2.0 W g^{-1}, 25°C), the second method incorporates the parallel use of microwave and spouted bed drying (2.0 W g^{-1}, 60°C) and the third one included the tandem combination of spouted bed drying followed by microwave. The third method produced potato cubes with highest rehydration and expansion ratio.

Table 2.8 Result of comparative study between microwave-spouted bed drying and spouted bed drying

Property	Microwave assisted spouted bed drying	Spouted bed drying
Bulk density	Decreased with increase in microwave power	No effect of air temperatures
Apparent density	Decreased with increase in microwave power	No effect of air temperatures
Bulk porosity	No effect of microwave power at particular temperature	No effect of air temperatures
Apparent porosity	Increased with increased in air temperature and microwave power	No effect of air temperatures
Sphericity	Increased with increase in microwave power	No effect of air temperatures
Color	L* value increased with increase in microwave power	L* and b* values decreased with increase in air temperature
Yield of bulgar	Decreased with increase in microwave power	No effect of air temperatures
Water absorption capacity	Effect of microwaves on water absorption capacity	No effect of air temperatures

There are several studies associated using the same concept such as drying of lettuce in which microwave assisted spouted bed drying was compared with other drying methods on the basis of physical properties (Y. F. Feng, Zhang, Jiang, & Sun, 2012), spouted bed drying of apple in which pre-treatment of ultrasound and microwave was compared (Mothibe, Zhang, Mujumdar, Wang, & Cheng, 2014) and spouted bed drying of sweet potato cubes in which various blanching method were studied as a pre-treatment (Liu, Mujumdar, Zhang, & Jiang, 2015; Liu, Zhang, & Mujumdar, 2014). In terms of energy efficiency, the study by Jindarat, Sungsoontorn, and Rattanadecho (2015) showed that drying of coffee beans with microwave assisted spouted drying was superior to spouted bed hot air drying. Huang et al. (2016) studied the hybrid technique in two and three stages for drying of carrot. The two-stage system consists of two microwave chambers in the first stage and one microwave chamber in the second stage. Three staged system comprised of four, two and one microwave chambers in first, second and third stage respectively. Drying rate was higher in the case of three stage drying and color change, chlorophyll and carotenoid content change were minimum. The cube dried with one and two-three stages had 75% and 81% rehydration capability respectively with better aroma.

2.7.5 Microwave assisted freeze drying

Freeze drying is one of the drying methods which is appropriate for products that are sensitive to heat (X. Duan, M. Zhang, A. Mujumdar, & R. Wang, 2010a; Genin & Rene, 1996). The main factor that encourages the use of freeze drying is the structural rigidity of the dried products which prevent the breaking of the final product after drying and provide good rehydration capability. Although freeze drying results in the dried product with good quality attributes still it is not widely used in industries due to its requirement for high capital (Liapis, Pim, & Bruttini, 1996). To cover up the disadvantage in freeze drying as well as in microwave drying, they are often combined to produce the dried product with low capital investment and good quality.

The microwave is combined with freeze drying in two possible ways. In the first one, the microwave is jointly used with freeze drying in which heat of sublimation is provided by microwave heat source (Duan et al., 2010a). These combinations result in the decrement of drying cost and increment of drying rates (R. Wang, Zhang, Mujumdar, & Sun, 2009; Wu et al., 2004). In the second method, the material is subjected to freeze drying until certain moisture level following which material is dried with either microwave or microwave vacuum drying for further reduction in moisture level. The latter process is more straightforward, but the technical parameter in this technique is the duration when the product is moved from one dryer to the other. Longer freeze-drying time would result in the sound quality of the end product, but it will add up to the drying time and cost. A good agreement among researchers on this technical parameter is noted wherein, the better quality of end product results (Duan et al., 2010a).

Various scholars across the globe have worked on the hybrid technique and have achieved noticeable useful results. In a study conducted by R. Wang et al. (2009), the effect of microwave power, material thickness and material loads was studied on the drying kinetics of instant vegetable soup mix. They concluded that an increase in power leads to a reduction in drying time, but the product quality was compromised. Drying time increased with an increase in material thickness and load, but too thin products had lousy quality at the end. Osmotic treatment as a pre-treatment for microwave assisted freeze drying of potato slices was studied by R. Wang, Zhang, and Mujumdar (2010). It was inferred that immersion of samples in the salt solution of different concentration (5, 10, 15%) leads to an increase in drying rate, but after 10% concentration, there was no effect on the drying rate. For sucrose solution of different concentrations (30, 40, 50%), drying rate was increased with an osmotic pre-treatment but no effect was visible on the drying rate when the sucrose solution concentration was above 40%. The equivalent results in the case of osmotic pre-treatment for microwave assisted freeze drying of restructured potato was also noted by R. Wang, Zhang, Mujumdar, and Jiang (2011). A comparative study between microwave assisted freeze drying and microwave assisted vacuum drying on potato and banana chips was carried out by H. Jiang, Zhang, Mujumdar, and Lim (2011). Microwave vacuum drying proposed shorter drying time, but the poor quality of end product and microwave assisted freeze drying offered good quality end product but with longer drying time. Effect of blanching on microwave freeze drying of plant material such as stem lettuce was studied by Yuchuan Wang, Zhang, Mujumdar, Mothibe, and Azam (2012). The result showed that microwave blanching is better than boiling in terms of drying time and product quality. Three drying techniques, i.e. freeze drying, microwave freeze drying and pulse spouted microwave freeze drying were compared in a study conducted by H. Jiang, Zhang, Mujumdar, and Lim (2014). Drying time was reduced by 50% in both microwave freeze drying, and pulse spouted microwave freeze drying, but the uniformity of heating was better in the case of pulse spouted microwave freeze drying. Rehydration ratio was better in the case of freeze drying than in microwave freeze drying or pulse spouted microwave freeze drying.

The relationship between glass transition temperature with moisture content and product temperature during microwave freeze drying was examined by Ren et al. (2015). Three power schemes of 1 kW, 2 kW and step-down microwave power were employed during the drying of mushrooms. The figure 2.7 shows the result of the drying concerning moisture content and temperature of the product. From the figure 2.7, it can be seen that as drying proceeds moisture content decrease and glass transition temperature increases. It is observed that if the product temperature is below glass transition temperature or if the difference between product and glass transition temperature is small it will exhibit low shrinkage and better quality. From the figure, it is seen that when applying step down power, the product temperature went down the transition temperature resulting in a decrease in overall shrinkage. Therefore, the conclusion was made so that the microwave power with step down facility will lead to a good trade-off between drying time and product quality.

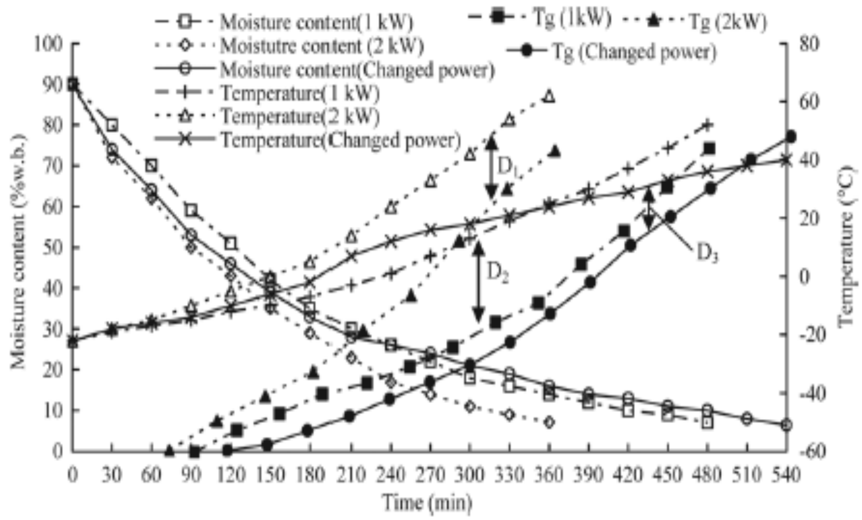


Figure 2.7 Moisture content and temperature profile of mushrooms undergoing microwave freeze drying. Reproduced from Ren et al. (2015), with permission from Taylor & Francis.

Microwave drying assisted by freeze drying has the disadvantage of plasma discharge occurring inside a vacuum chamber which results in burning of food material, excessive consumption of microwave energy and leading to non-uniformity inside a microwave cavity (X. Duan, M. Zhang, A. S. Mujumdar, & S. Wang, 2010b; Lombrana, Zuazo, & Ikara, 2001). Plasma discharge happens due to the ionization of the gases present inside a vacuum chamber when the electric field intensity reaches above a threshold value. For industrial applications, there should exist a good control over process parameters like microwave power and pressure inside the vacuum chambers (M. Zhang et al., 2006). Scholars have presented several solutions to address this issue such as studying of corona discharge at different microwave power and pressures to predict a control strategy (Duan, Ren, & Zhu, 2012; Duan et al., 2010b), use of superheated vapor produced from the water in the circular conduits jacket (Yuchuan Wang, Zhang, Mujumdar, & Mothibe, 2012), using microwave on off cycle with up down in vacuum pressure which could result as being a controllable parameter (Lombrana et al., 2001).

2.7.6 Microwave assisted infrared drying

The moisture accumulated on the surface of food material due to microwave drying is removed through infrared power in microwave assisted infrared drying (A. Datta & Ni, 2002; Tireki, Şumnu, & Esin, 2006). Halogen lamps are used in combination with microwave drying in cases where the moisture content have to be reduced to lower values (Tireki et al., 2006). Infrared drying cause heating at the surface of the drying material which further leads to the transfer of heat towards the center of the material due to conduction (Łechtańska et al., 2015; Nowak & Lewicki, 2004). Due to this, infrared drying is efficient during constant rate drying period at which there is the availability of moisture on the surface of the drying material (Kowalski & Rajewska, 2009; Łechtańska et al., 2015). Infrared radiations fall into three categories: near infrared (0.75-3.00 µm), far infrared (25-100 µm) , medium infrared radiations (3.00-25 µm) (Ratti & Mujumdar, 2014). Scholars have employed near (Dondee, Meeso, Soponronnarit, & Siriamornpun, 2011; Sumnu, Turabi, & Oztop, 2005; J. Wang & Sheng, 2006), far (Nimmol, Devahastin, Swasdisevi, & Soponronnarit, 2007; J. Wang & Sheng, 2006) and medium radiation (Q. Chen et al., 2015; Haoyu et al., 2013) for the drying of various biomaterials.

Infrared drying assisted with microwave drying is a new technique and several studies have been conducted in this exciting area. In their research, Kantrong, Tansakul, and Mittal (2014) studied the drying kinetics of shiitake mushroom with microwave vacuum assisted by far-infrared power (FIR). Microwave vacuum drying and microwave vacuum assisted infrared drying experiment was carried out at different microwave power, vacuum pressure and FIR power. The result showed that drying time reduced with an increase in microwave power, a decrease in absolute pressure and an increase in FIR power. Usually, a drop in absolute pressure results in a reduction in the boiling point of water, causing vaporization at a much lower temperature, which in turn causes a decrease in drying time (Saengrayap, Tansakul, & Mittal, 2015). In terms of color, microwave vacuum assisted infrared drying of mushrooms resulted in a darker product with higher redness and yellowness. The possible reason noted by the authors for the above effect was the occurrence of non-enzymatic reaction at higher drying temperature. Rehydration ratio, hardness and shrinkage can be achieved better in the case of microwave vacuum drying of red chili assisted by infrared. Łechtańska et al. (2015) scrutinized five different combinations of the microwave, convective and infrared in the drying of green pepper. Convective drying (CV), convective drying assisted with microwave (CVMW), convective drying assisted with microwave and periodically assisted with infrared drying (CVMW+ IR_{per}), convective drying periodically assisted with microwave and infrared drying (CV + MW_{per} + IR_{per}) and convective drying periodically assisted with infrared (CV + IR_{per}) were the treatments used in the study. The outcome reported that the drying time was highest in CV and lowest in CVMW+ IR_{per}. The water activity (a_w) which is directly correlated with the shelf life of the product was lowest in the case of CV + IR_{per} but this combination resulted in high energy consumption and low quality of the end product. CVMW resulted in minimum energy consumption and highest retention of vitamin C.

Microwave assisted infrared drying was also studied by Aydogdu et al. (2015) where this combination was clubbed with osmotic dehydration for drying of eggplant. The surface temperature of the product was higher, and the drying time was shorter in the case of microwave assisted infrared drying. The value of effective moisture diffusivity (D_{eff}) in the case of convective drying was less than that in the case of microwave assisted infrared drying, but the osmotically treated sample resulted in less D_{eff} than untreated ones. The possible justification of this could be the less driving force due to a low moisture content in the case of osmotic dehydration pre-treatment.

2.7.7 Microwave multi flash drying technique

Multi flash drying technique is a new emerging technology in the field of drying, which involves heating of material up to a certain temperature at atmospheric pressure followed by a vacuum pulse which further leads to cooling and evaporation of moisture content (Laurindo, Porciuncula, & Zotarelli, 2011; Link et al., 2017). This method has an advantage of producing crispy dried products such as fruits and vegetables and in many cases can be used as an alternative to freeze drying (Laurindo et al., 2011; Link et al., 2017; Zotarelli et al., 2012). The three types of multi flash drying depending on the heating source are listed in Table 2.9.

Table 2.9 Types of multi flash drying (Link et al., 2017; Link, Tribuzi, & Laurindo, 2018; Ricardo Lemos Monteiro et al., 2018; Zotarelli et al., 2012)

Drying type	Mechanism
Convective multi-flash drying	• Hot air is used to heat the food material followed by a vacuum pulse. • Pressures higher than atmospheric are not required during the process.
Conductive multi flash drying	• Heated plates are used for the heating of the food material followed by cycles of vacuum.
Microwave multi flash drying	• Microwave energy is employed for the heating of the food material followed by vacuum pulse.

Researchers have employed conductive (Link, Tribuzi, de Moraes, & Laurindo, 2018; Link et al., 2017; Link, Tribuzi, & Laurindo, 2018) and convective (Zotarelli et al., 2012) multi flash drying for drying of food material. In the case of microwave multi flash drying, Monteiro, Carciofi, and Laurindo (2016) employed the concept for drying of bananas and compared it with microwave vacuum and freeze drying. The drying time was found less, and drying rate was found more in the case of microwave vacuum drying than microwave multi flash drying. The reason behind this could be the high continuous microwave power in the case of microwave vacuum drying. Freeze drying and microwave vacuum drying resulted in changes in the structure of bananas, but microwave multi flash drying did cause some important changes such as large pores. This can be explained as drying proceeds; moisture loss leads to the development of capillary pressure inside the porous food material which further leads to shrinkage of the food material. But in the case of multi flash drying, flash evaporation leads to the sudden expansion of the gases, which balances the capillary pressure inside the porous food material and reduce shrinkage. Crispiness was found more in the case of microwave multi flash drying and increase in porosity was high in the case of multi flash drying due to puffing effect resulting from each heating-vacuum cycle. Comparable results were reported by Ricardo Lemos Monteiro et al. (2018) and Ricardo L Monteiro, Jade V Link, Giustino Tribuzi, Bruno AM Carciofi, and João B Laurindo (2018) in microwave multi flash drying of pumpkin slices compared to microwave vacuum, freeze, air and conductive multi flash drying. Pumpkins dried by microwave multi flash drying were crispier than any other method. Both the multi flash drying resulted in lower color change and both microwave methods resulted in a more porous dried material.

2.7.8 Intermittent microwave power technique

Intermittent drying of food product leads to better utilization of microwave energy and maintain a good quality of the dried product. The continuous supply of energy result in less drying time, but energy consumption is less in the case of intermittent operation (Shivhare, Raghavan, Bosisio, & Mujumdar, 1992). Drying uniformity and various quality parameters during pulsed microwave drying was studied by Yuchuan Wang, Zhang, Mujumdar, Mothibe, and Roknul Azam (2013).

The study concluded that pulse operation of microwave energy resulted in a more uniformly dried product as compared to the continuous process. Color difference (ΔE) was lowest in pulsed operation and there was no significant difference in shrinkage between continuous and pulsed operation of the microwave. Concerning microstructure, wrinkles were found on the surface of stem lettuce dried by microwave vacuum drying and vacuum drying but were not significant during pulsed operation. In a study conducted by Nema12, Mohapatra, Daniel, and Mishra (2013) drying kinetics of ginger in pulsed microwave assisted convective drying was studied. Apart from this effect of microwave power and the power off time on drying kinetics was also reported and the results showed that higher microwave power resulted in shorter drying time and higher power off time resulted in a more energy efficient process. Mothibe, Wang, Mujumdar, and Zhang (2014) compared microwave assisted pulse spouted drying with microwave assisted spouted drying, microwave vacuum drying and conventional vacuum drying, and it was inferred that microwave assisted spouted drying gave the highest drying rate and rehydration capacity, but the product was harder. Therefore, microwave assisted pulse spouted drying was concluded to be the best methods for drying products with high quality. Chandan Kumar, Joardder, et al. (2016) developed a mathematical model for pulsed microwave assisted convective drying for apple and it was depicted that drying time was shorter in the case of pulse operation. Nair et al. (2011) studied the seed germination capability of corn after three drying methods of constant temperature, constant power and intermittent power. The results concluded that drying time was less in the case of constant power drying, but seed germination rate as shown in figure 2.8 was highly hampered. In the case of intermittent power, drying time was less than that of constant temperature and the equal seed germination rate was achieved.

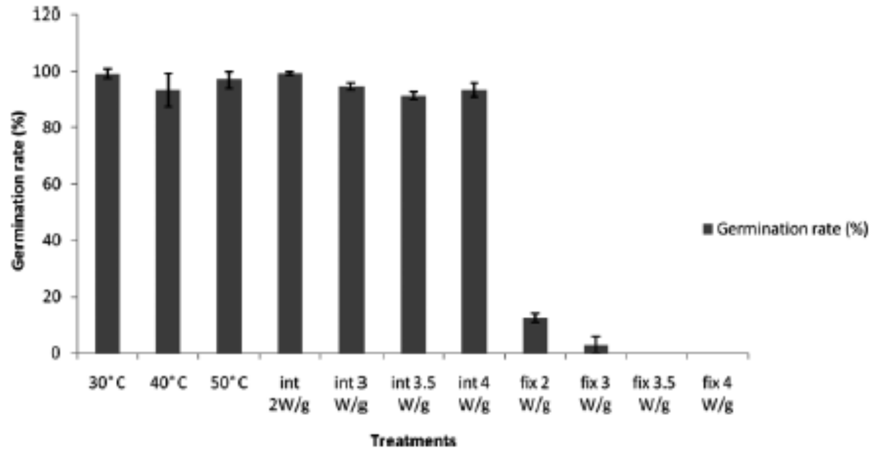


Figure 2.8 Seed germination rate of corn undergoing drying under various scheme. Reproduced from Nair et al. (2011), with permission from Taylor & Francis.

2.8 Non uniform temperature distribution during microwave heating

Non uniformity of the electromagnetic waves which often leads to the non-uniform heating of the material result in the cold and hot spots within the material. Non-uniformity is caused by the geometry and the concentration of the drying material or by the propagation pattern of microwaves inside the microwave cavity (H. Feng et al., 2012). In connection with the geometry of the material, for example, microwaves reaching the surface of the food material will decay while reaching the center resulting in boundary to receive more radiations or the situation where the microwave incident on two different sides of material will lead to overheating of the core. Regarding microwave propagation in the cavity, the waves get reflected from the metallic cavity and form a complex network of waves leading to hot and cold spots inside the sample. Concerning the concentration of the food material, areas with abundant moisture will attract more microwave energy and will lead to non-uniformity inside the sample (H. Feng et al., 2012).

This non uniformity has been studied by various researchers worldwide and several solutions have been suggested. H Feng and Tang (1998) found that the spouted bed instead of the stationary bed had resulted in more uniformity in temperature. Yang and Gunasekaran (2001) reported that the hot spot in the center of agar gel samples as a result of microwave drying was not evident when the experiment was run with pulsed microwave drying. Lau and Tang (2002) showed that the frequency of 915 MHz resulted in more uniform heating and less operating time. Dai, Orsat, and Raghavan (2010) have employed gypsum plates dipped in cobalt chloride solution to map the distribution patterns of the microwave in the commercial multimode microwave cavity. Dried gypsum plates had a red color when immersed in a cobalt chloride solution and the loss of water (or heating) from the plates resulted in light pink or blue spots on the gypsum plate. This method despite of successfully mapping the pattern was also cost effective. The information on the distribution patterns at different locations in the cavity can help food processing industries with various operations like drying or pasteurization. Geedipalli et al. (2007) showed that using a turntable for placing the sample can increase the uniformity of temperature by 40%. According to Pitchai, Birla, Jones, and Subbiah (2012), uniform heating is achieved in a microwave cavity by placing the sample, not at the center, but at the edges of turntable whereas Madhuchhanda Bhattacharya and Basak (2017) showed that the shape of the food sample (circular or square) plays an important role in distributing heating patterns. For the thin samples, both the shapes were uniformly heated, but for the thick samples, the square shape should be industrially preferred. Furthermore, H. Zhang, Hayert-Bonneveau, Yout, Helstern, and Loizeau (2005) invented the device that would lead to more uniform heating in a microwave cavity. The patent includes the container with a supporting cavity in which food material of particular shape and size is placed. The peripheral walls of the cavity are shielded with microwave reflective material and when subjected to microwaves leads to more uniform heating due to the application of changing wavelengths on the food material.

2.9 Microwave equipment's at an industrial scale

Domestic microwave systems are different from industrial equipment in both size and microwave power rating. Unlike domestic microwave ovens, microwave generator is used separately at an industrial scale which produces the microwave which are further transferred into the cavity through waveguide. Several types of microwave drying equipment's are available for various raw material in industries, for example continuous microwave tunnel drying. In these dryers, microwave generators are used for the production of microwaves that travel to the cavity with the help of the waveguide. Often these designs contain antennas that help in distributing microwaves uniformly in the cavity. The system consists of one or more microwave cavity and the product is passed through it with the help of the conveyor. At an industrial scale, programmable logic controllers are used for the control of the process. Equipment also provide control over microwave power, belt speed and temperature. All the microwave system parts are made from non-toxic and high temperature resistant material (Information retrieved from cellencor.com and maxindustrialmicrowave.com). Another example is microwave batch drying which are simply the higher power unit than the domestic microwave ovens. In industries, they are usually used for the processing of smaller amount of the food products. Sometimes a hybrid technique is used which employ conveyor with a batch microwave system for the feeding of material. Sometimes batch microwave ovens consist of the cavity with loading table on rollers and products can be loaded onto the table for processing (Information retrieved from ferriteinc.com). Nowadays, industries are also using microwave vacuum dryers which instead of using box type microwave vacuum drying system, employ continuous operation vacuum drying system. The continuous systems are fully automated and easy to operate in large scale production. Microwave vacuum freeze drying industrial equipment has a system of preventing glow discharge which could occur during vacuum drying. Hence, it maintains the freeze-drying environment and product quality better than a vacuum or freeze drying separately. Table 2.10 display a list of various products and the industrial system available for drying.

Table 2.10 Industrial microwave system for various products

Product	Equipment available	Source of information
Packed instant noodles, fruit and vegetable	Industrial microwave machine for drying and sterilization	Max industrial microwave
Food powder products such as flour starch etc.	Microwave conveyor or tunnel dryer	Max industrial microwave
Herbs, tea, flower or spices	Microwave conveyor dryer	Max industrial microwave
Any food product not to dry above 100 °C	Microwave vacuum dryer	Max industrial microwave
Small amount of material	Microwave batch oven	Max industrial microwave
Herbal extract, food, pharmaceutical and chemical product	Microwave vacuum belt dryer	Puschner microwave power systems
Food product	Batch, semi batch, continuous conveyor or tunnel type microwave systems	Kerone
Large objects or bio-composites	Indexing batch microwave system i.e. combination of batch and conveyor system	Cellencor
Liquids and powder	Mixers or paddles attached along with microwave system	Cellencor

Powders and ceramics and pharmaceutical products	Microwave system combined with hot air or steam or vacuum	Sairem
Powder, granular or slurries	Microwave systems with agitated bed	Marion process solutions
Production of syngas from biomass waste	Microwave plasma system	Plasma kraft and plasma technologies
Edible insects	Microwave continuous conveyor or tunnel and batch system	L'Entomofago

2.10 New emerging trends in microwave technology

New technology employing solid state generators instead of magnetrons for the production of microwave are capable of providing potential advantages in food processing industries. In these generators, a small microwave signal is generated through RF generator and these signals are fed into a high-power amplifier. This high-power amplifier is connected to a DC power supply. It consists of step-down transformer which reduces the AC voltage value to a desired level, a rectifier circuit which generate single polarity pulse signal and a filter circuit which converts AC to pure DC which is further supplied to a high-power amplifier. The power supplier with DC power converts low microwave power signal to high microwave signal which is further fed into the microwave cavity (Atuonwu & Tassou, 2018). Since the commercialization of microwaves at domestic as well as industrial level, magnetrons have been used for the production of microwaves, but they offer certain disadvantages which can be rectified through solid state generators. These generators offer a longer lifespan than magnetrons (Wesson, 2015) and have low operational voltage and smaller size (Schwartz, Anaton, Huppert, & Jerby, 2006). Also, different food material absorbs different amount of microwave energy and solid state generators provide an advantage to alter the frequency of microwave and this in turn leads to more uniform heating (Atuonwu &

Tassou, 2018). Solid state generators also offer good power and phase control which handle the issue of non-uniformity. Commercialization of microwave technology is often hindered due to its various disadvantages such as non-uniform heating. Future research employing solid state in microwave technology will give an insight on its effect on issues related to uniformity, food safety and energy consumption.

2.11 Conclusion

This review has presented the basics of microwave drying such as dielectric properties, the heating mechanism, mathematical modelling along with addressing the problem of non-uniformity of electromagnetic waves. Moreover, several hybrid techniques of microwave drying along with recent developments have been demonstrated. Various hybrid or multi-stage drying techniques have proven profitable in covering up disadvantages offered by conventional methods. Most optimized drying methods for any product depend on various factors such as quality of the end product, drying time, energy consumption and various physical and chemical changes occurring during drying. Intermittent microwave techniques including multi flash drying offer an extra edge over continuous operation and has acclaimed a lot of attention in recent years. At the end of the study, an idea of studying the effect of using solid state generators on drying or other microwave processing technology is presented. The development of technology which will be energy efficient as well retaining good quality of food products is needed and the challenges of implementing these techniques at an industrial scale should also be kept in mind.

Connecting Text

In this review paper basics of microwave drying such as drying mechanism, dielectric properties and mass transfer calculations have been studied. Also, each microwave drying technique with its recent development and different variety of products dried have been reported in the review paper. It was observed that the application of microwave drying in the drying of seed grade grains such as soybean seeds was low except few studies reporting microwave drying in seeds. The following chapter reports the investigations of drying of soybean seeds in a continuous thin layer microwave drying assisted by air. Various seed quality parameters such as germination percentage, vigor index along with fissure percentage have been studied after the drying step.

Chapter III Effect of Microwave Assisted Air Drying on the Drying Kinetics and Germination Potential of Soybean Seeds

3.1 Abstract

Microwave assisted air drying of the soybean seeds was conducted in this study and various quality and physiological parameters such as germination, vigor index, fissure and cracking were tested after drying. Drying was carried out at different microwave powers (0, 50 and 100 W) and air temperatures (30, 40 and 50 °C). The seeds were rewetted to the moisture content of 21% (wb) and drying was continued till a final moisture content of 11% (wb) was achieved. Drying kinetics, modelling and effective moisture diffusivity was calculated from the experimental data. The influence of process variables and their interaction was studied through face centered response surface methodology. Drying time was significantly reduced by using microwave due to higher drying rates. Modelling of the data predicted that exponential model fits well with the experimental data and the effective moisture diffusivity increased with increase in microwave power and air temperature. The germination potential and vigor profile of the seeds were greatly affected by this drying technology. Seeds dried with 50 and 100 W of microwave power at three air temperatures were recorded to have germination percentage less than 35%. Fissure and cracking percentage were observed to have been increased with rise in microwave power and air temperature. The maximum permissible microwave power density and temperature which resulted in 75% germination of seeds was 0.04 W/g and 40 °C respectively.

Keywords: Microwave drying; soybean seed; germination; vigor; drying kinetics

3.2 Introduction

Soybean is currently one of the major agricultural commodity as it is a great source of protein for human as well as animal consumption (Rafiee et al., 2009). Acquiring higher yield and lower harvesting cost as compared to other grains has made soybean one of the significant food sources at the global scale (Felipe & Barrozo, 2003). Operations after harvesting of soybean depend on whether it will be used for processing, feeding or as a seed for planting. After harvesting, high-quality soybean seeds are subjected to drying, cleaning, grading and storage for planting purpose (Marcos-Filho & McDonald, 1998). Low seeds moisture content is essential for longer storage and maintaining good seed quality because they lose viability and vigor at higher moisture content. Numbers indicate that about 25% of stored seeds are lost due to their poor quality and low viability (M. Barrozo et al., 2014).

Soybean, to be used as a seed for next year crop production has certain qualities that are prerequisite for a great harvest and are emphasized by the seed industry. Seeds should have high germination, high vigor and well-developed seat coat for proper development. However, various processing methods such as drying leads to deterioration of seed quality which in turn contributes to crop losses.

The published literature to date related to the topic in question contain many studies which focus on soybean drying such as in microwave assisted air dryers (Ranjbaran & Zare, 2012), fluidized bed dryer (Darvishi, Khoshtaghaza, & Minaei, 2015) or microwave assisted fluidized bed dryers (Khoshtaghaza, Darvishi, & Minaei, 2015). However, all these studies are related to the drying of soybean which is further used for industrial applications. Shivhare et al. (1993) studied the microwave drying and the germination potential of soybean seeds and result showed that power density of 0.13 W/g can be used for microwave drying of the seeds. Microwave drying has been used on many other seeds such as corn (Shivhare, Raghavan, & Bosisio, 1991; Shivhare, Raghavan, & Bosisio, 1992; Shivhare, Raghavan, Bosisio, et al., 1992), rapeseed (Łupińska et al., 2009), cottonseed (Wesley et al., 1974) and wheat (Y. Li, Zhang, Wu, & Zhang, 2014; Manickavasagan, Jayas, & White, 2007). In a study conducted by M. Barrozo, Felipe, Lacerda, and Lisboa (2005); Felipe and Barrozo (2003) and M. A. S. Barrozo et al. (1998) drying of soybean seed in different moving bed dryers was carried out and various seed quality parameters were studied.

In the current study, lab-scale microwave assisted air drying of soybean was carried out at different process variables and seed quality was studied post drying. The main objectives of this study are as follows:

1. To find out the effect of various process variables on the drying kinetics and quality of seeds.
2. To optimize the drying method for maximum product quality that will lead to better resource of planting seeds.

3.3 Materials and Methods

3.3.1 Materials

OAC CALYPSO soybean cultivar from Quebec, Canada was used for the experimental purpose. The initial moisture content of the soybean seeds was calculated by the oven-drying method by putting the seeds in the oven for 72 hours at 105°C (Standard, 2001). The initial moisture content of the soybean seeds was 7.02% (wb). Therefore, a rewetting step to increase the moisture content was used to increase it up to 21% (wb). In this process, a known amount of soybean seeds was taken in a glass container and a calculated amount of water was added to it. The glass containers were then placed in the refrigerator at a temperature of 12°C for three days (Nair et al., 2011). The glass containers were shaken twice a day for uniform absorption of water. The drying procedure was carried out by taking 120 g of soybean seeds with 21% (wb) moisture content and drying until the moisture content reached 11% (wb). The average diameter of 20 soybean seeds was 5.68 mm measured through micrometer. The rewetted samples were placed at room temperature for 30 minutes before drying in each run.

3.3.2 Drying

3.3.2.1 Microwave drying at 2450 MHz

Microwave drying of soybean seeds was carried out in a laboratory scale microwave dryer assisted with hot air and controlled through a computer program as shown in Figure 3.1. The main components of the whole setup were microwave generator, waveguides, three port circulator, manual three stub tuner for matching load impedance, microwave couplers that measures transmitted and reflected power, a carbon load to absorb microwave power, fiber optic probes and microwave cavity for drying. Microwave generator (Gold Star 2M214, Seoul, South Korea) was having variable power from 0 to 750 W and was adjusted according to the required power using a scale on the generator. Rectangular waveguides (TE10 mode, 72 * 35 mm size) was used for the transfer of microwaves from the generator to the cavity. Microwave cavity was made of brass of dimensions 47*47*27 cm. Fiber optic probes (Nortech EMI-TS SERIES, Quebec City, Canada) were used for recording the core temperature of the product. The whole system was monitored, and various control parameters were controlled by HP VEE (Agilent) object-oriented programming. The microwave cavity also contains Teflon basket on which product was placed for drying and the basket was connected to electronic balance which was used to measure the weight of samples during drying. The independent variables chosen for the microwave assisted convective drying of soybean seeds were air temperature (AT) and microwave power density (PD).

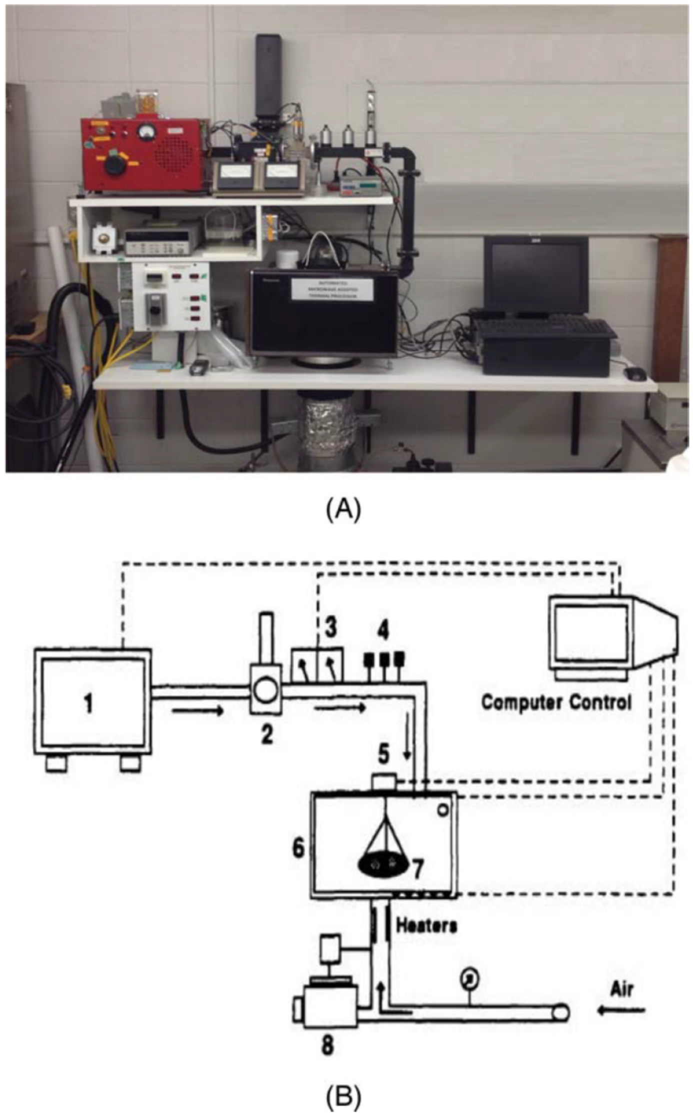


Figure 3.1 (A) Microwave assisted laboratory dryer (B) Schematic diagram of Microwave assisted air dryer; (1) Microwave generator (2) Circulator (3) Power meters (4) Tuning screws (5) Strain gauge (6) Microwave cavity (7) Sample holder (8) Blower; Reprint with permission

3.3.2.2 Experimental design

Response surface methodology was employed to find the contribution of the above variables on the drying kinetics and quality of soybean seeds. Fourteen drying runs were carried out, which were designed according to the face-centered central composite design with three levels of each variable. The levels of each variable in actual and coded forms are shown in Table 3.1 and various combinations of the drying run according to the aforementioned design is shown in Table 3.2.

Experiments were randomized and the center point was replicated six times to reduce the variability. Design Expert version 11 was used for the analysis of variance and designing of the experiments.

Table 3.1 Levels of microwave assisted air drying variables

Variable	Name(unit)	Level		
		-1	0	+1
AT	Air Temperature (°C)	50	60	70
PD	Power Density (w/g)	0	0.5	1.0

Table 3.2 Face Centered central composite design level combinations

Experiment No.	Variable combination	
	AT	PD
1	-1	-1
2	1	-1
3	-1	1
4	1	1
5	-1	0
6	1	0
7	0	-1
8	0	1
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0

3.3.3 Mathematical modelling of drying data

Drying kinetics is fully explained by the properties like thermal and moisture diffusivity, mass and heat transfer coefficients. However, sometimes the drying rate constant is used as a combination of these to standardize a processing mechanism (Giri & Prasad, 2007; A. S. Mujumdar & Menon, 1995).

To characterize a moisture ratio as a function of drying time, two mathematical models were considered. The Newton model, Eq. (13) and the Page model, Eq. (14) have been used to describe the drying kinetics of various agricultural and food products (Giri & Prasad, 2007; Kardum, Sander, & Skansi, 2001; Prabhanjan et al., 1995; Sharma & Prasad, 2001). In this study, both the models were tested for their validity in microwave assisted convective drying of soybean seeds.

$$\mathrm{MR} = \mathrm{EXP}(-\mathrm{K} \times \mathrm{t}) \quad \text{.......(13)}$$

$$\mathrm{MR} = \mathrm{EXP}(-\mathrm{k} \times \mathrm{t}^{\mathrm{n}}) \quad \text{......(14)}$$

Moisture ratio (MR) which is (M-M_e) / (M_o-M_e), where M is moisture content at any time t, g water/ g dry matter; M_o is initial moisture content, g water/ g dry matter; M_e is the equilibrium moisture content, g water/ g dry matter and t is the drying time, min. The final moisture content of the seeds was used as the equilibrium moisture content in the drying of seeds in the microwave assisted air dryer (Prabhanjan et al., 1995; Sharma & Prasad, 2004).

The parameters K, k and n were determined through nonlinear regression carried out in SPSS software program. The goodness of fit was determined through the coefficient of determination (R^2), chi-square χ^2, and root mean square error (RMSE). The highest value of R^2 and lowest value for χ^2 and RMSE best describes the drying conditions.

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(\mathrm{MR}_{\mathrm{exp}} - \mathrm{MR}_{\mathrm{pre}}\right)^2}{\mathrm{N} - \mathrm{z}} \quad \text{......(15)}$$

$$\mathrm{RMSE} = \left(\frac{1}{\mathrm{N}} \sum_{i=1}^{n}\left(\mathrm{MR}_{\mathrm{exp}} - \mathrm{MR}_{\mathrm{pre}}\right)^2\right)^{0.5} \quad \text{......(16)}$$

Where MR_{pre} is predicted moisture ratio, MR_{exp} is experimental moisture ratio, N is the number of observations and Z is the constants in the drying model.

3.3.4 Effective moisture diffusivity

Drying is the combination of heat and mass transfer process and thermal energy. It is important to remove moisture from the surface of seeds. In the case of convective drying thermal energy is imparted through the hot air and in the case of microwave drying, heat is generated through the volume of the seed kernel (Ranjbaran & Zare, 2012).

For moisture transport, diffusion is considered as the dominant process in the case of food materials (Souraki & Mowla, 2008). The mathematical model used in this study was based on Fick's law of diffusion (Dadalı et al., 2007; Ranjbaran & Zare, 2012) :

$$\frac{\partial M}{\partial t} = \nabla^2 (D_{eff} M) \qquad \text{.......(17)}$$

where M is the moisture content, t is the drying time (s) and D_{eff} is the effective moisture diffusivity (m^2/s). Considering the spherical coordinates and constant value of D_{eff}, the following equation can be rewritten as:

$$\frac{\partial M}{\partial t} = \left(D_{eff} \frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r}\right) \qquad \text{.......(18)}$$

where r is the radius of the seed kernel (m).

The theoretical solution of the above equation can be obtained by following assumptions and boundary conditions (Cranck, 1975; Dadalı et al., 2007; Ranjbaran & Zare, 2012).

1) Boundary conditions used were as follows:
    a) Moisture at the surface before drying is M_o (initial moisture content)
    b) And after drying time of t is M_e (equilibrium moisture content).
2) Diffusion is the primary source of moisture migration in the seeds kernel.
3) Diffusion coefficient as well as temperature is constant and the shrinkage of kernels during drying is negligible.
4) Resistance to moisture migration is negligible in accordance with the internal resistance and mass transfer is symmetric.

The solution to the above equation, keeping in mind all the boundary conditions and assumptions is as follows:

$$MR = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-D_{eff}\, n^2 \Pi^2}{r^2} t\right) \qquad \text{....... (19)}$$

The above equation will be reduced to the first term of the series and researchers have claimed that this reduction doesn't have a significant effect on the prediction of diffusivity value (Doymaz & Pala, 2003).

$$MR = \frac{6}{\pi^2} \exp\left(\frac{-D_{eff}\pi^2}{r^2} t\right) \quad \text{....... (20)}$$

Eqn. 6 was evaluated for Fourier number, $F_o = D_{eff} * t/r^2$ for diffusion and can be rewritten as

$$\ln MR = \ln\left(\frac{6}{\pi^2}\right) - F_o \pi^2 \quad \text{.......(21)}$$

For π = 3.14, the Eqn. 7 takes the following form

$$F_0 = -0.0504 - 0.1014 \ln MR \quad \text{.......(22)}$$

where, $F_o = D_{eff} * t/r^2$ and

$$D_{eff} = \frac{F_o r^2}{t} \quad \text{.......(23)}$$

Effective moisture diffusivity was calculated by substituting the positive values of F_o (calculated through Eqn. 23) and drying time corresponding to each moisture ratio along with a radius of soybean kernel (Dadalı et al., 2007). The average effective moisture diffusivity was calculated by taking the average of diffusivity values at different times.

3.3.5 Seed quality

3.3.5.1 Germination test

Germination test provide information about how the seed will emerge under favorable weather and soil conditions (B. Kumar, Verma, Ram, & Singh, 2012). The test was carried out by the rolled paper towel method. Fifty seeds were placed on the paper towel moistened with distilled water in a ratio of 2.5 times the mass of dry paper. The wet paper along with seeds is then placed in a germinator at 25°C in an upright position in a jar for eight days. Distilled water up to 3 cm from the bottom was added periodically to keep the paper moistened. On the 8th day, the percentage of seeds germinated or normal seedlings were counted and the germination rate was expressed as a percentage of seeds germinated to the total seeds placed (Reddy et al., 1998).

3.3.5.2 Seedling Vigor index

Seed vigor is an indication of the tolerance power of seed under harsh conditions at the time of germination and it is also an indicator of a success or a failure of a crop (B. Kumar et al., 2012). There can exist a situation where seeds can germinate, but the seedling is not developed properly.

Ten normal seedlings from the germination test were taken and their shoot and radicle length (cm) was measured by the ruler (Sheidaei, Abad, Hamidi, Nour, & Mohammadi, 2014). Seedling vigor index was calculated by the following relation.

Seedling vigor index= (Mean of radicle length + Mean of shoot length) x final germination percent

3.3.5.3 Seed Fissure and cracking test

Drying of seeds involves evaporation of water on the outer layer of the kernel which in turn causes contractions in the layer due to the compression caused by atmospheric pressure. Often, drying temperature leads to the expansion of internal layers of kernels due to increase in internal pressure. When the temperature increases, developed shear stress caused fissures and cracks (Menezes, Cicero, Villela, & Bortolotto, 2012). The Hypochlorite test was used to find the non-fissured seeds after drying treatment. Seeds after drying were submerged in a 5% solution of sodium hypochlorite. After 7 minutes, the number of swollen and fissured seeds were calculated and fissure index was expressed in percentage (Felipe & Barrozo, 2003).

Cracking of the soybean kernels was studied by sorting out the cracked kernels visually using light (Darvishi et al., 2015). The cracking percentage can be calculated by the following equation:

$$Cracking\ percentage = \frac{m_c}{m_s} \times 100 \qquad ....(24)$$

where m_c is the mass of cracked kernels in g and m_s is the total mass of kernels

3.4 Results and Discussion

3.4.1 Drying kinetics

In this section, results of microwave assisted air drying at different microwave power density and air temperature levels are presented and discussed. The drying curves for microwave assisted air drying of soybean seeds are presented in Figure 3.2, where moisture ratio as a function of the time interval for various process parameters is presented. The drying time required to reduce the moisture level to an acceptable limit depends on both power as well as air temperature. It was observed that increasing power and temperature resulted in a decrease in drying time. The time required to decrease the moisture content from 21% wb to 11% wb was least in microwave drying at 50 °C and 100 W (18.77 min) and highest in air drying at 30 °C (155.73 min). Seeds having 21% initial moisture content were dried to a final moisture content of 11% within 47.23 and 18.77

min at a microwave power of 50 and 100 w respectively, at air temperatures of 50°C. Drying was eight times faster for seed samples dried using microwave than the seeds dried without a microwave (zero power), thus resulting in a 88% reduction in drying time. Łupińska et al. (2009) reported the same reduction in drying time during microwave drying of rapeseeds.

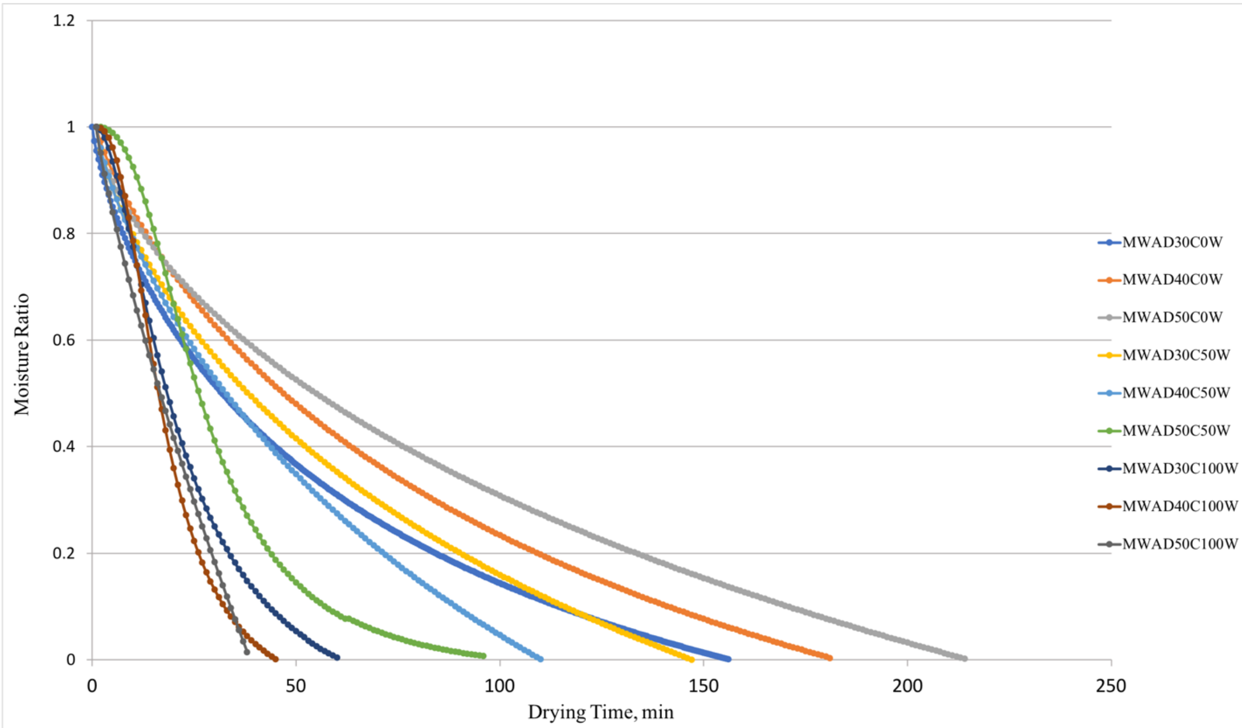


Figure 3.2 Drying curve for microwave assisted air drying of soybean

The effect of two process variables, microwave power density (PD) and air temperature (AT) was studied on the drying time through response surface methodology and fitting the experimental value of drying time in a second order polynomial. The analysis of variance (ANOVA) is shown in Table 3.3 and the regression model for the response is shown in Table 3.4. The model was found significant at 1% along with a high R^2 value of 0.9761 and lack of fit insignificant. From the ANOVA, it can be seen that for drying time, the both linear and quadratic term of the model is significant at 1 % and 5 % respectively. The effect of microwave power density was found to be more significant than air temperature as depicted by high corresponding F values. The cross product of both the process variable was also found significant at 5 %. The variation of drying time with the microwave power density and air temperature is shown in Figure 3.3.

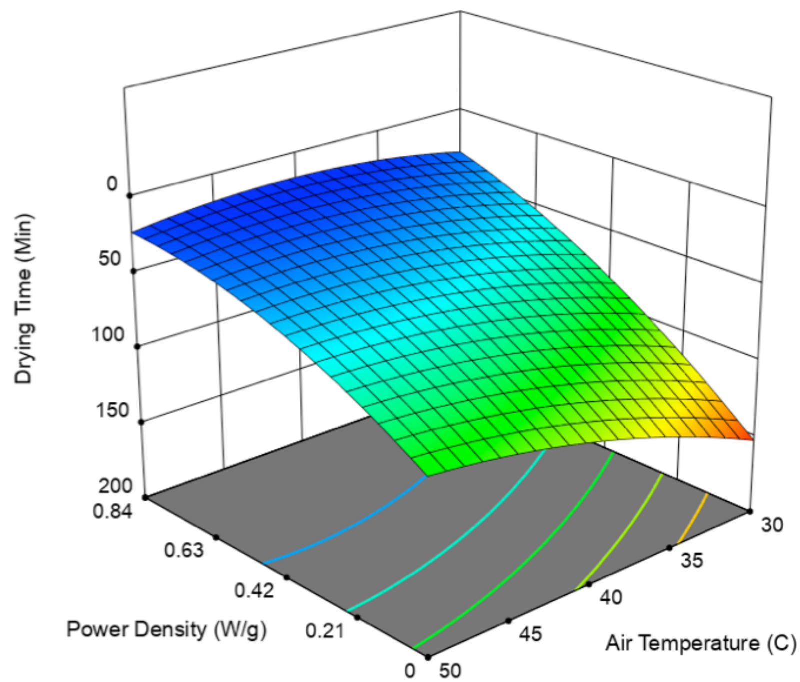


Figure 3.3 Effect of air temperature and microwave power on drying time

Drying rate as a function of time for different treatments is shown in Figure 3.4. The accelerated drying rate associated with the microwave was due to internal heat generation and high vapor pressure inside the grain kernel. As the drying proceeds, the drying rate follows a decreasing trend due to the reduction in the seeds moisture content. It should also be noted that the variation in the microwave power has a more significant effect than the variation of temperature on the drying rates. At zero microwave power, change in temperature didn't cause significant changes in the drying rate. However, at 50 and 100 W, an increase in temperature caused significant changes in drying rate. Also, the effect of the variation of process parameters is more prominent in the early stages of drying.

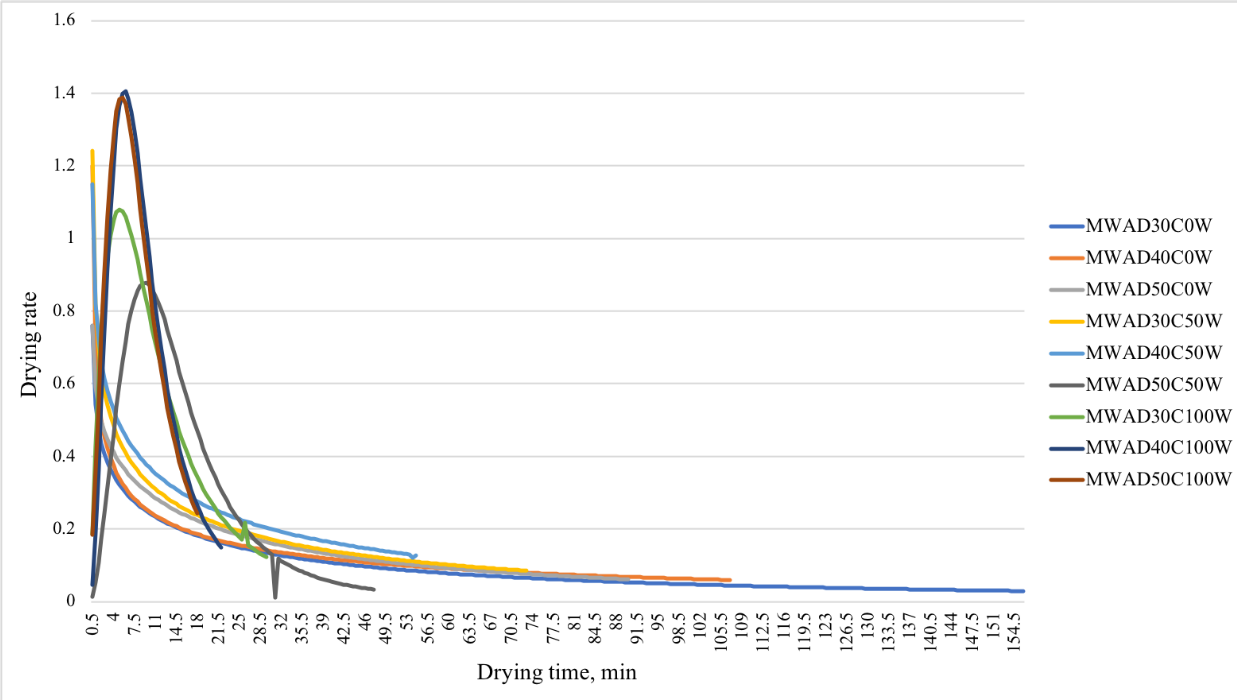


Figure 3.4 Drying rate curves for microwave assisted air drying of soybean

Table 3.3 ANOVA showing the linear, quadratic and cross product effect of the process variables on study parameters

Source of Variation	df	Drying Time		Germination Percentage		Fissure Percentage		Vigour Index		Drying Constant		Diffusivity		Cracking Percentage	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Model	5	3441.13	65.27*	2349.85	107.36*	1244.6	148.6*	4.3E+05	83.75*	0.0034	57.01*	227.96	130.48*	78.55	82.54*
AT	1	1747.63	33.15*	163.70	7.48**	522.67	62.4*	22990.9	4.52	0.0011	18.74*	106.60	61.02*	1.14	1.20
PD	1	13257.76	251.47*	9547.27	436.2*	4816.87	575.08*	1.6E+06	314.78*	0.0143	239.24*	885.74	506.98*	384.48	403.99*
AT^2	1	280.79	5.33**	33.03	1.51	1.41	0.1686	8396.17	1.65	4.142E-07	0.0069	0.1785	0.1022	1.90	1.99
PD^2	1	576.56	10.94**	1465.71	66.97*	532.25	63.55*	3.5E+05	70.29*	0.0012	20.66*	92.09	52.71*	2.11	2.22
AT*PD	1	757.08	14.36**	2.79	0.1274	210.25	25.10*	7859.71	1.54	0.0001	1.67	31.73	18.16*	0.2862	0.3008
Residual	8	52.72		21.89		8.38		5087.32		0.0001		1.75		0.9517	
Lack of Fit	3	39.39	0.6168	16.33	0.6474	8.5	1.02	7906.32	2.33	0.0001	1.59	2.94	2.85	0.4140	0.3249
Pure Error	5	60.72		25.22		8.30		3395.92		0.000		1.03		1.27	
Total	13														

df-Degree of freedom; MS-Mean square; AT-Air temperature; PD-Power density
* Significant at 1%.
** Significant at 5%.

Table 3.4 Regression analysis model for different response during microwave assisted convective drying of soybean seeds

Response	Second order polynomial regression model	R^2
Drying Time	$393.383 - (11.05 \times AT) - (310.87 \times PD) + (3{,}275 \times AT * PD) + (0.099 \times AT^2) + (80.86 \times PD^2)$	0.9761
Germination Percentage	$154.8 - (3.17 \times AT) - (195.33 \times PD) - (0{,}1988 \times AT \times PD) + (0.034 \times AT^2) + (128.93 \times PD^2)$	0.9853
Fissure Percentage	$-2.49 + (0.773 \times AT) + (63.68 \times PD) + (1.73 \times AT \times PD) - (0.0071 \times AT^2) - (77.7 \times PD^2)$	0.9893
Vigor Index	$2317.7 - (54.17 \times AT) - (3343.93 \times PD) + (10.55 \times AT \times PD) + (0.544 \times AT^2) + (2013.93 \times PD^2)$	0.9813
Drying constant	$-0.0045 + (0.00056 \times AT) - (0.031 \times PD) + (0.0012 \times AT \times PD) + (3.823E - 06 \times AT^2) + (0.118381 \times PD^2)$	0.9727
Diffusivity	$3.31 - (0.061 \times AT) - (25.041 \times PD) + (0.6705 \times AT \times PD) + (0.0025 \times AT^2) + (32.32 \times PD^2)$	0.9879
Cracking Percentage	$12.97 - (0.59 \times AT) + (17.5 \times PD) - (0.064 \times AT \times PD) + (0.0081 * AT^2) + (4.9 \times PD^2)$	0.981

AT-Air Temperature; PD-Microwave power Density

3.4.2 Modelling of microwave assisted air drying data for soybean

Table 3.5 shows the value of the exponential model and the page model parameters when applied to the experimental data of the microwave assisted air drying of soybean seeds. A good fit as represented by high R^2 and low χ^2 and RMSE value was obtained for all process conditions. The drying constant value calculated through exponential model showed a range of 0.021 for 30 °C 0W to 0.111 min^{-1} for 50 °C 100W. It can be seen that the drying rate constant value showed a rising trend with an increase in air temperature and power level. It should also be noted that at a constant temperature, application of microwave significantly increased the drying rate constant value from 0.021 min^{-1} at 0 W to 0.09 min^{-1} at 100 W. The values of the rate constants are in good agreement with those reported by Ranjbaran and Zare (2012) for microwave assisted air drying of soybean.

The response surface plot for the drying rate constant is shown in Figure 4.5 along with the analysis of variance shown in Table 3.3. From ANOVA, it can be seen that the model is found to be significant at 1 % and R^2 (0.9727) along with lack of fit to be insignificant. The regression analysis of drying rate constant yielded the second order polynomial model shown in Table 3.4.

Linear terms of both the parameters were found to be significant; however, the quadratic term related to air temperature was not found significant. The effect of microwave power density was more significant than air temperature for drying rate constant.

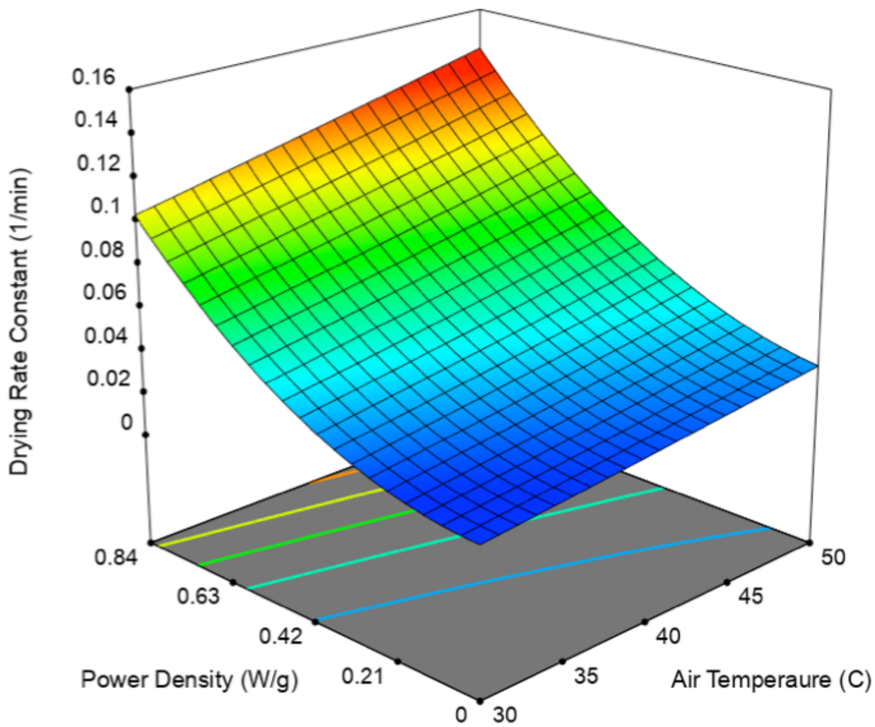


Figure 3.5 Effect of air temperature and microwave power on drying rate constant

Table 3.5 Statistical results of mathematical modelling of drying curves

Air Temperature (°C)	Microwave power (W)	Exponential Model Parameters				Page Model Parameters				
		K (min^{-1})	R^2	χ^2	RMSE	k (min^{-1})	n	R^2	χ^2	RMSE
30	0	0.021	0.989	0.000699659	0.026408773	0.03	0.912	0.992	0.000471546	0.02164562
40	0	0.026	0.992	0.000997243	0.031505622	0.029	1.013	0.992	0.003159191	0.05594464
50	0	0.031	0.984	0.00054204	0.023217343	0.032	0.947	0.985	0.000593146	0.02421965
30	50	0.038	0.988	0.000766795	0.027596714	0.04	0.984	0.988	0.000763926	0.02745055
50	50	0.064	0.94	0.006663978	0.081206904	0.01	1.653	0.997	0.00036048	0.01878749
30	100	0.09	0.964	0.003660027	0.059991887	0.031	1.423	0.999	7.30078E-05	0.00840084
40	100	0.108	0.917	0.010186822	0.099802045	0.017	1.804	0.999	0.00012863	0.0110866
50	100	0.111	0.96	0.004567833	0.083464983	0.048	1.327	0.986	0.00028474	0.0185739
40	50	0.056	0.985	0.001169023	0.033993915	0.035	1.157	0.993	0.000583725	0.02388107
40	50	0.051	0.973	0.002273671	0.047417378	0.021	1.285	0.994	0.000531231	0.02279092
40	50	0.052	0.965	0.003104138	0.055389918	0.017	1.363	0.996	0.00040523	0.01989487
40	50	0.046	0.987	0.000931894	0.030387869	0.038	1.064	0.988	0.000827289	0.02849995
40	50	0.04	0.94	0.006040525	0.077414222	0.006	1.573	0.994	0.000103715	0.01010352
40	50	0.042	0.944	0.006056155	0.077427269	0.008	1.469	0.989	0.000976027	0.03092425

3.4.3 Calculation of effective moisture diffusivity coefficient

The logarithm of moisture ratio (ln MR) was plotted against drying time (t) at different process conditions and is shown in Figure 3.6. From the figure, it is noted that the relationship between ln MR and time is not linear under all drying conditions. This non-linearity in the figure can be due to possible reasons such as shrinkage associated with dried product, non-uniform initial moisture distribution, change in the temperature of product or variation in the moisture diffusivity along with moisture content (Adu & Otten, 1996; Khraisheh, Cooper, & Magee, 1997; Sharma & Prasad, 2004). In the initial stage of drying, liquid diffusion was a major source of moisture transport in the kernels as depicted by a straight line in Figure 3.6. However, as the drying proceeds further, vapor diffusion was a dominant source of moisture transport. A second order polynomial was used to find the relationship between ln MR and drying time t as shown below:

$$\ln MR = (A \times t^2) + (B \times t) + C \quad \text{……(25)}$$

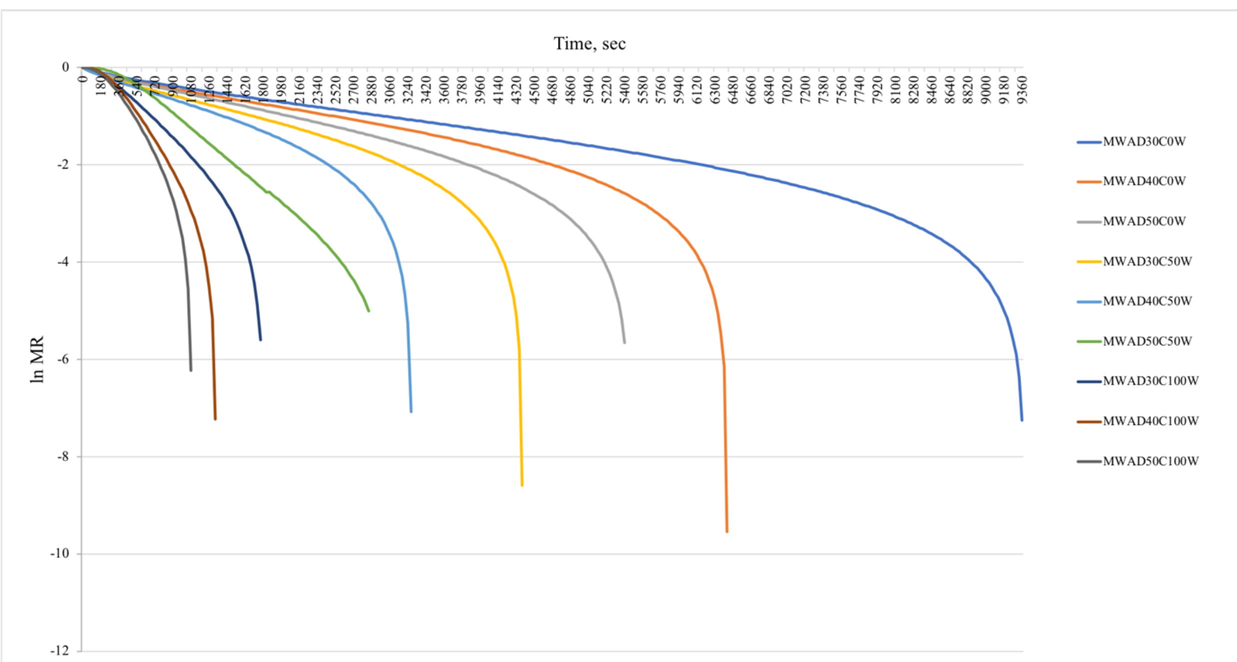


Figure 3.6 Logarithmic of moisture ratio versus time

The values of coefficients A, B and C calculated through nonlinear regression analysis along with R^2 values are presented in Table 3.6.

Table 3.6 Regression coefficients and coefficient of determination value at different treatments

Microwave power (W)	**Air Temperature (° C)**	**Regression coefficient**			
		A	B	C	R^2
0	30	-0.00004	0.0005	-0.4284	0.9361
0	40	-0.00009	0.0027	-0.4148	0.9381
0	50	-0.0001	0.0009	-0.3364	0.9556
50	30	-0.0002	0.0078	-0.4687	0.8752
50	40	--0.0005	0.0065	-0.292	0.9542
50	50	-0.0000002	-0.001	0.1663	0.9971
100	30	-0.0012	-0.0041	-0.1166	0.9765
100	40	-0.0031	0.0319	-0.2124	0.944
100	50	-0.000003	0.0009	-0.2615	0.9482

The values of moisture diffusivity corresponding to positive values of F_o were plotted against the moisture content (dry basis) and is presented in Figure 3.7. From the Figure, it can be seen that moisture diffusivity increases with a decrease in moisture content under all process conditions. Sharma and Prasad (2004) and Bouraoui, Richard, and Durance (1994) have also reported an increase in moisture diffusivity with a decrease in moisture content. This means that as the moisture content decreases over time, permeability to vapor increases, as the pore structure remained open. A third order polynomial was used to find the relationship between diffusivity and moisture content as shown below and the value of coefficients and R^2 is shown in Table 3.7.

$$D_{eff} = (A \times M^3) + (B \times M^2) + (C \times M) + D \quad \text{......(26)}$$

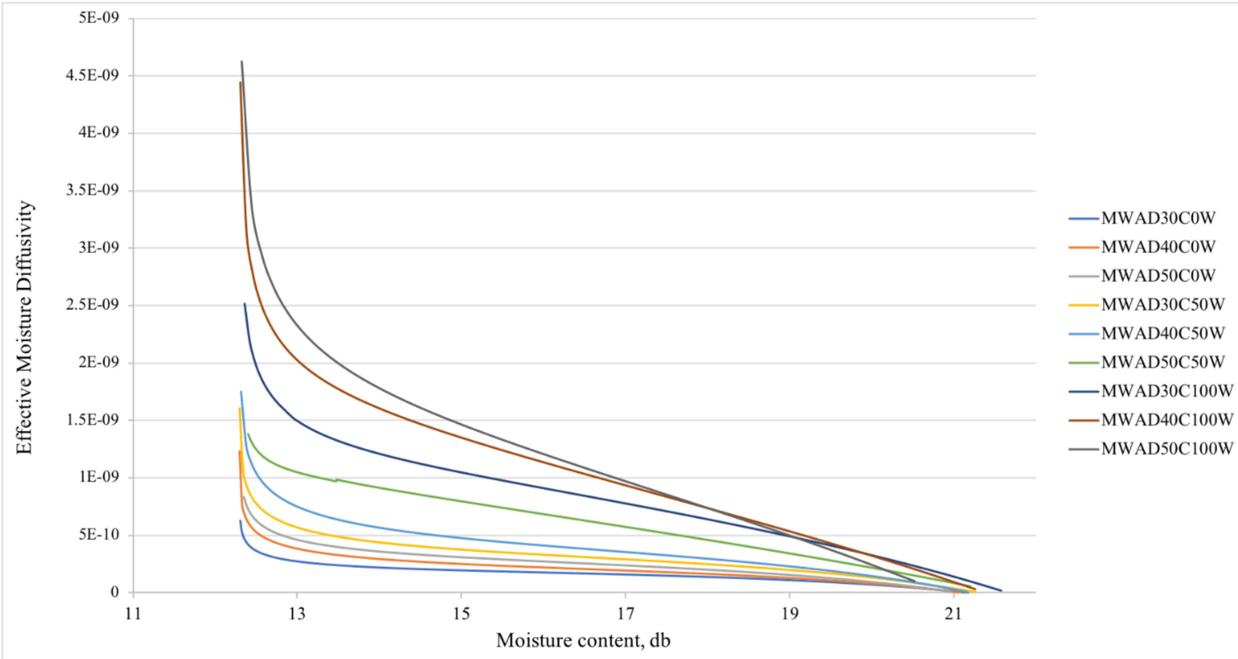


Figure 3.7 Variation of moisture diffusivity along with the moisture content

Table 3.7 Regression coefficients and coefficient of determination value for moisture diffusivity at different treatments

Microwave power	**Air temperature**	**Regression coefficient**				
		A	B	C	D	R^2
0	30	-0.04225	2.14295	-36.327	209.03	0.9142
0	40	-0.05475	2.8073	-48.228	281.185	0.947
0	50	-0.0626	3.1925	-54.61	317.885	0.9571
50	30	-0.0927	4.78425	-82.46	480.16	0.8582
50	40	-0.1152	5.9655	-103.33	605.15	0.9074
50	50	-0.0524	2.677	-47.356	300.14	0.9852
100	30	-0.14315	7.473	-131.48	793.35	0.9543
100	40	-0.2894	15.093	-263.47	1556.55	0.8854
100	50	-0.1746	9.044	-166.26	1125.9	0.9915

The effect of various process variables was studied through response surface methodology. The analysis of variance (ANOVA) is shown in Table 3.3 along with the response plot shown in Figure 3.8. The second order polynomial as shown in Table 3.4 was found to be significant at 1% with an R^2 value of 0.9879 and lack of fit insignificant. Linear terms of both process variable, the quadratic term related to microwave power density and cross product of both the variables were found to be significant at 1%. Diffusivity has shown a great dependence on microwave power density and the value of average effective moisture diffusivity has increased with increase in microwave power density as well as air temperature. The value of average effective moisture diffusivity ranges from $2.04*10^{-10}$ to $17.6*10^{-10}$ m^2/s for soybean, which is in good agreement for food materials having diffusivity in the range of 10^{-11} to 10^{-9} m^2/s (Zogzas, Maroulis, & Marinos-Kouris, 1996).

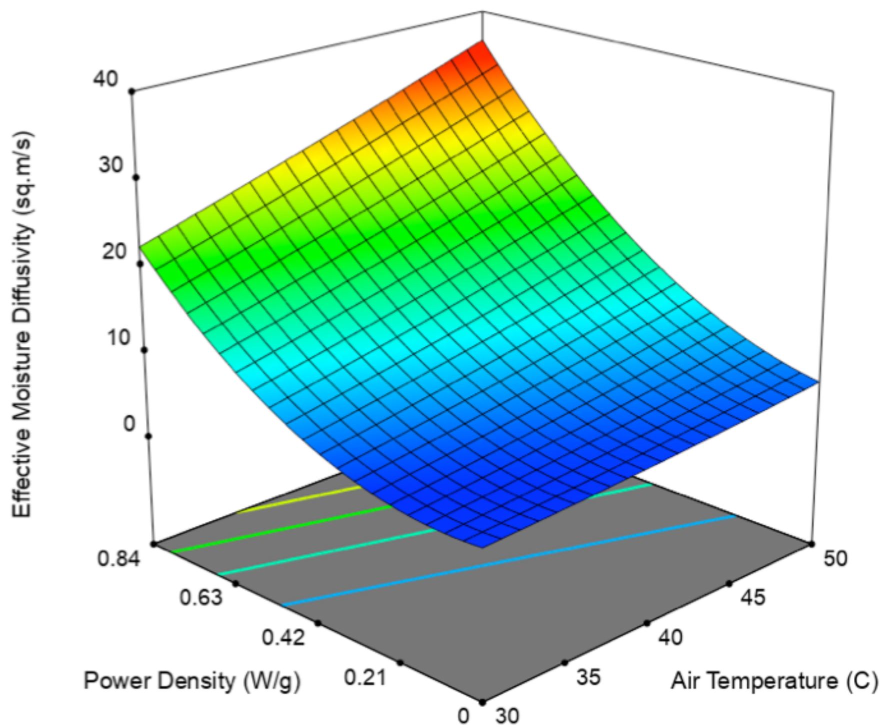


Figure 3.8 Effect of air temperature and microwave power on average effective moisture diffusivity

3.4.4 Seed quality parameters

3.4.4.1 Seed germination

Germination tests were carried out in a roll paper towel method and the results at various process conditions are shown in Figure 3.9. From the results, it can be seen that maximum germination percentage was achieved at 30 °C 0 W (88.67%) followed by 40 °C 0W (83.34%) and 50 °C 0W (83.34 %). Unfortunately, the seeds dried at a microwave power of 50 W and 100 W, at three air temperatures did not germinate and the percentage of germination was below 35% for the respective treatments. Łupińska et al. (2009) also reported the loss of germination potential by using the microwave for drying of rapeseeds. Shivhare et al. (1993) reported that microwave can be used for the drying of soybean with the power density of 0.13 W/g and below.

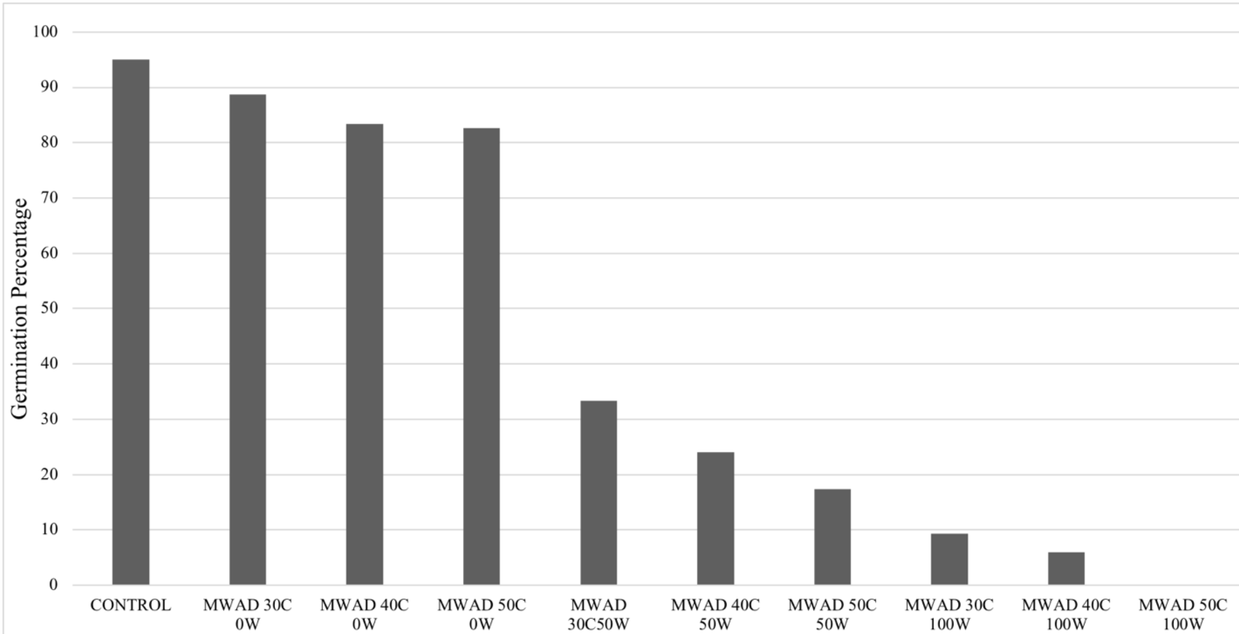


Figure 3.9 Germination percentage at various treatments during drying of seeds

The effect of air temperature and microwave power density studied through response surface methodology is shown in Figure 3.10 and the analysis of variance (ANOVA) is shown in Table 3.3. The model shown in Table 3.4 was found significant at 1% with an R^2 value of 0.9853 and the lack of fit insignificant. Microwave power significantly affected the germination potential of seeds as depicted by the significant linear and quadratic term with high F values.

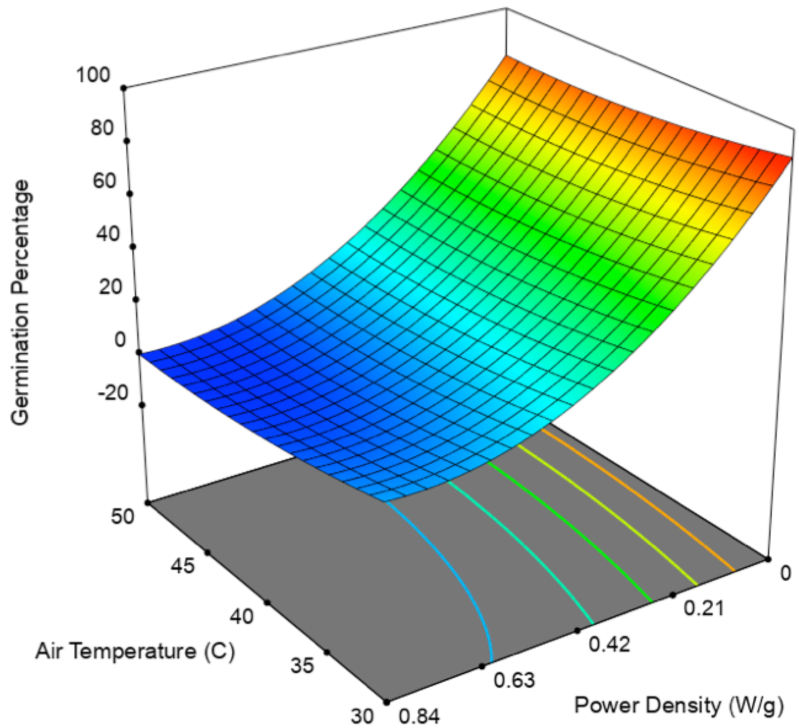


Figure 3.10 Effect of air temperature and microwave power on germination potential of seeds

Volumetric heating due to microwave may have interacted with the protein and carbohydrates present in the seeds. As protein, carbohydrates and sugar content help in the germination process of the seeds. It was inferred that the microwave may have caused protein denaturation in the kernel resulting in a suppression of sprouting ability of the seeds. However, microwave drying has resulted in a significant reduction in the drying time and the dried seeds can be used for industrial purposes such as oil extraction. The annihilation of germination potential of the seeds is an advantage in the storing of seeds for industrial application.

3.4.4.2 Seedling vigour index

Seed vigor was calculated with the help of seedling length (root + shoot) and was represented in terms of seed vigor index as shown in Figure 3.11. It was noticed that the vigor index for the seeds decreased with an increase in microwave power density and air temperature. The response surface model was found significant at 1% with an R^2 value of 0.9813 and lack of fit insignificant. The response surface plot is shown in Figure 3.12 and the regression model relating parameters with vigor index is shown in Table 3.4.

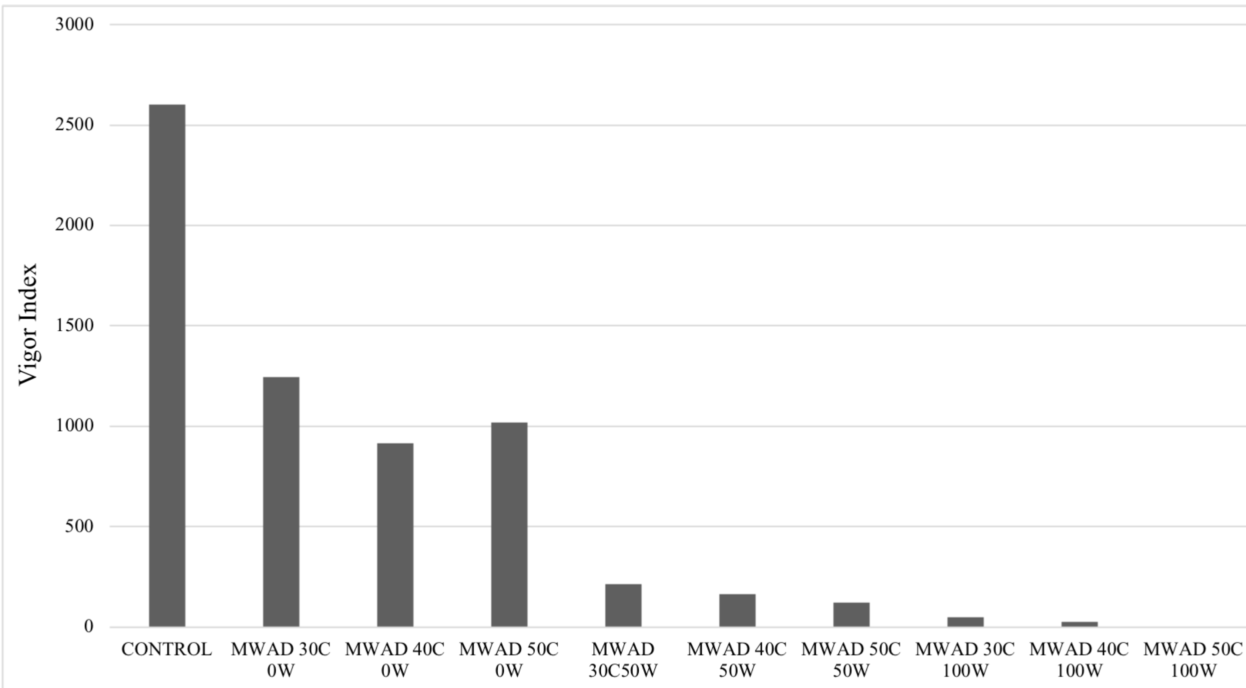


Figure 3.11 Vigor index value at different treatments

The analysis of variance shown in Table 3.3 depict that the microwave power had significantly affected the performance of crop due to low germination and small seedling length. Air temperature didn't have a significant effect on the vigor index of seeds.

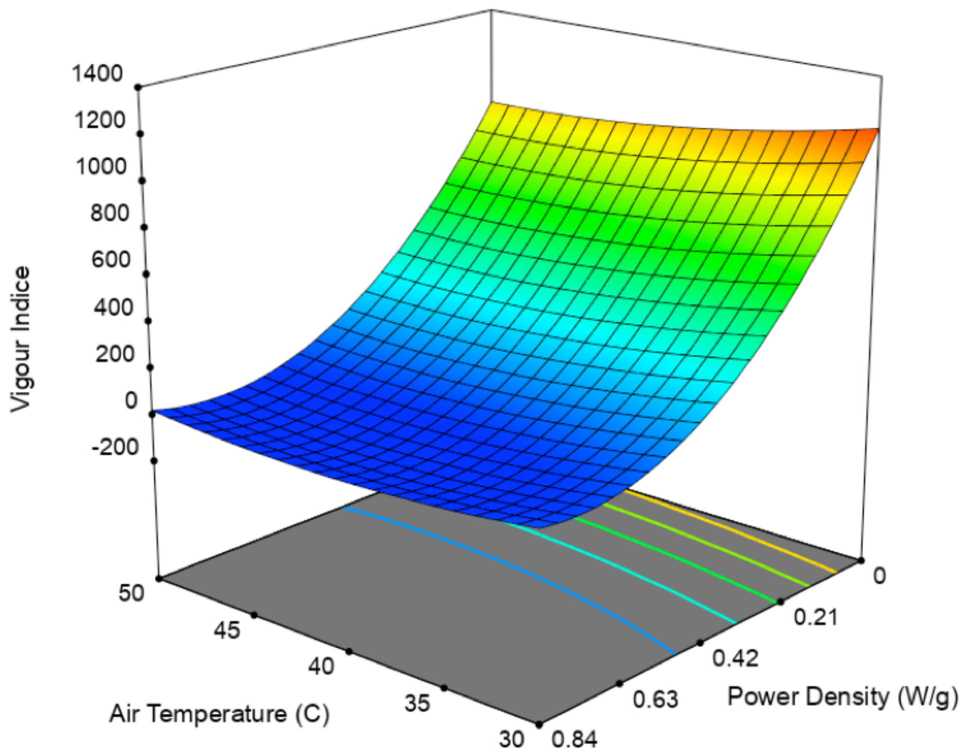


Figure 3.12 Effect of air temperature and microwave power on vigor index of seeds

3.4.4.3 Fissure and cracking percentage

Fissured seeds were tested through sodium hypochlorite solution and the cracked seeds were inspected visually. Fissured and cracked soybean seeds are shown in Figure 3.13 (a) and 3.13 (b) and the percentage of both at different treatments are shown in Figure 3.14. Fissured seeds tested through sodium hypochlorite solution are shown in Figure 3.15, where on the left are the fissured seeds and on the right are the non-fissured seeds. It can be seen that as the temperature and power density is increased, fissures and cracked seeds have increased. This could be due to the higher rate of water loss from the kernel without leaving an interval for the moisture to redistribute inside the kernel resulting in a humidity gradient (Menezes et al., 2012). This could also explain the loss of germination potential at high microwave power density. Figure 3.16 (a) and 3.16 (b) shows the response plot for fissure and cracked percentage and the analysis of variance is shown in Table 3.3. The regression model relating process variables for both responses is shown in Table 3.4.

(a) (b)

Figure 3.13 Visual representation of (a) fissure and (b) cracked seeds

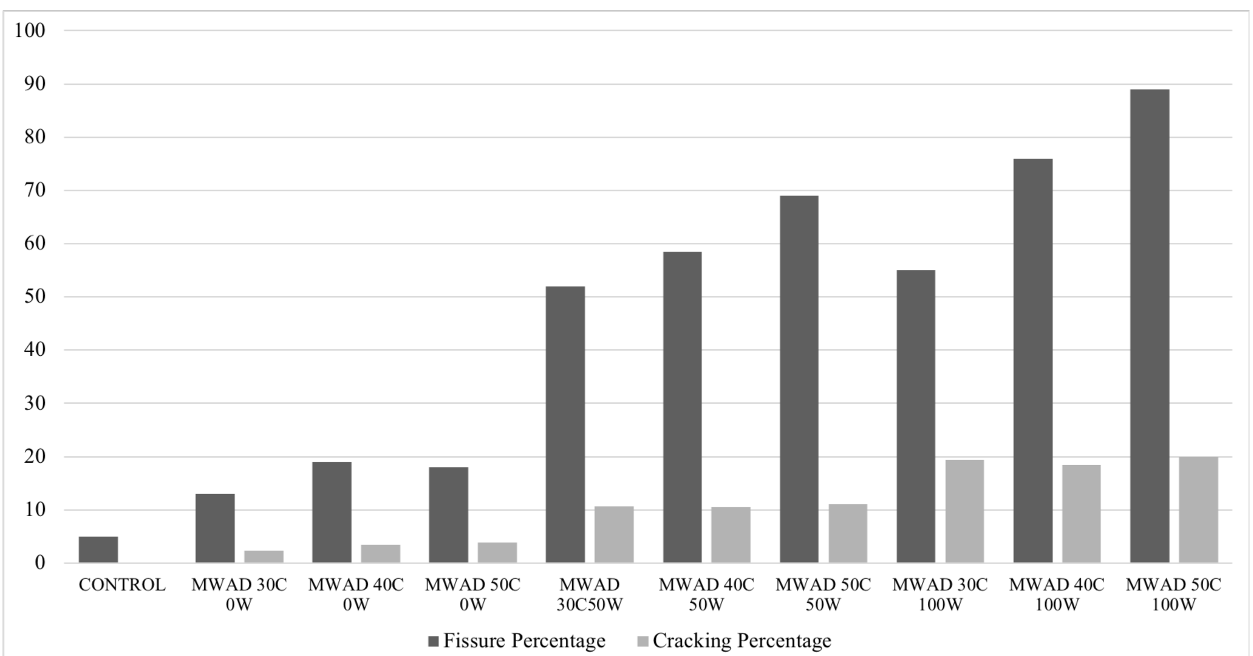
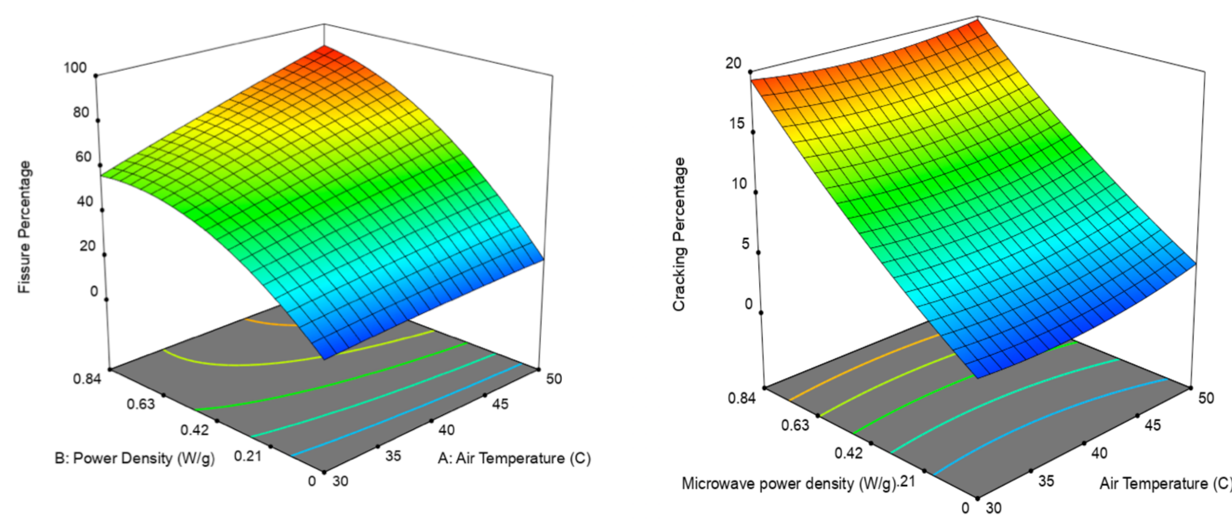


Figure 3.14 Percentage of fissure and cracked seeds at different treatments

Figure 3.15 On left fissured seeds and on right non-fissured seeds after sodium hypochlorite test



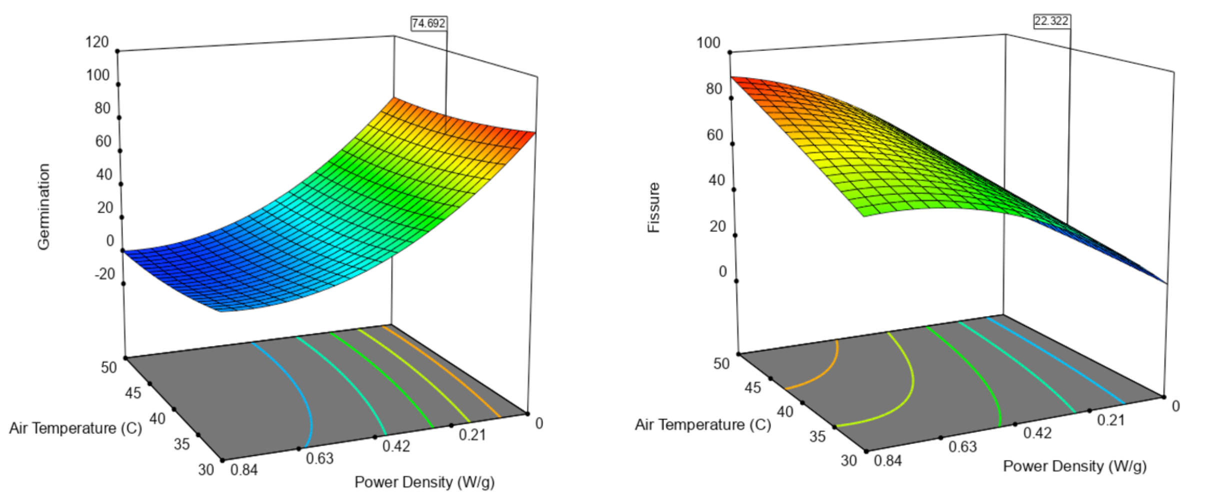
(a) (b)

Figure 3.16 Effect of air temperature and microwave power on (a) fissure and (b) cracking percentage

Models were found significant at 1% with high R^2 values and lack of fit insignificant for both responses. From the ANOVA of fissure percentage, it can be seen that linear terms for both process variable were found significant. However, the effect of microwave power density was more significant on fissure percentage than the air temperature. For cracking percentage, air temperature of 30, 40 and 50 °C didn't have a significant effect on cracking of seeds, but the effect of microwave power density was found significant for both quadratic as well as linear term.

3.5 Optimization

Optimization of the drying process was carried out in Design Expert version 11 to find an optimum condition for processing of soybean seeds. Germination percentage, fissure percentage, vigor index, cracking percentage and drying time were included for optimization. Germination percentage target was set in between 75 to 80% and the value of other responses were calculated as shown in Figure 3.17. It was noted that for 75% of germination in seeds, optimum microwave power density was 0.04 W/g and air temperature was 39 °C.



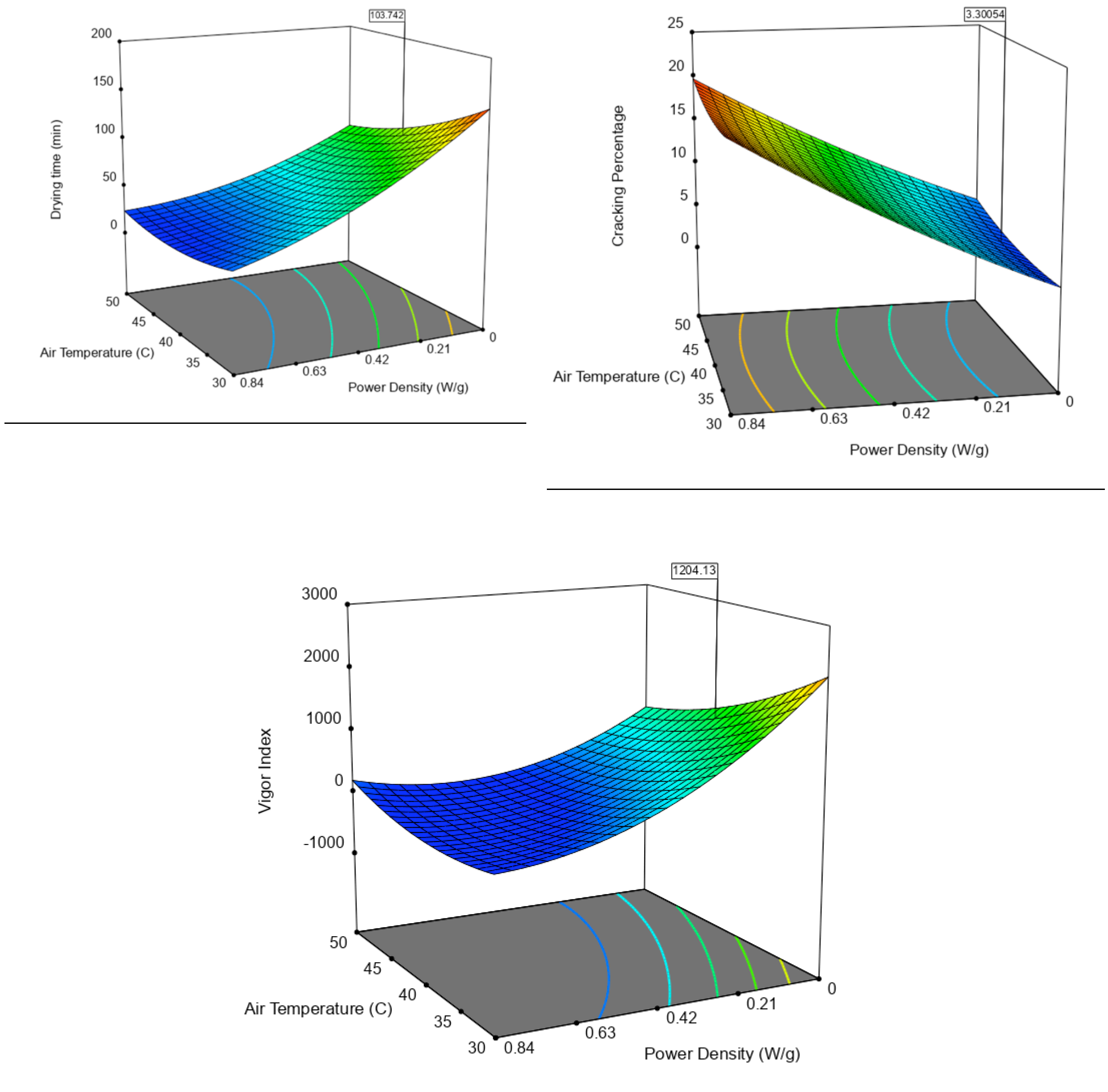


Figure 3.17 Value of each response at optimized conditions

3.6 Conclusion

The drying characteristics and quality of soybean seeds under microwave assisted air drying were studied. Application of microwaves resulted in lower drying time and higher drying rates. Exponential and page model was used for the prediction of the moisture ratio during drying of soybean seeds. Effective moisture diffusivity was calculated through Fick's law of diffusion and was in the range of $2.04*10^{-10}$ to $17.6*10^{-10}$ m^2/s. Microwave dried seeds were not able to germinate and had a high percentage of fissures. Since the reduction in drying time was 80 %, microwave dried seeds can be used for industrial purpose instead of planting purpose. Optimized condition for the drying was at an air temperature 39 °C and microwave power density 0.04 W/g. Application of optimum conditions resulted in 106 min of drying time along with 75% of germination, 1204.13 vigor index, 3.3% of cracking and 22% of fissured seeds. Seed grade soybean can be obtained by incorporating appropriate microwave field intensity and future research could include intermittent or multi stage microwave application during drying of soybean.

Connecting Text

In the previous section thin layer microwave assisted air drying of the seeds and seed quality was discussed and it was seen that thin layer drying leads to the seeds with no germination capability and high seed coat damage. In the following section, fixed bed and fluidized bed drying of seeds was carried out and after that microwave was incorporated in the fluidized bed to reduce the drying time and the seed quality was studied after the drying stage.

Chapter IV Effect of Fluidized Bed and Microwave-Assisted Fluidized Bed on the Drying of Seed Grade Soybean

4.1 Abstract

Soybean seeds were dried under fluidized and microwave assisted fluidized bed drying conditions in this study. During fluidized bed drying, the effect of air temperature (30-50 °C) and air velocity (1-7 m/s) on drying parameters and some quality attributes (viz. Vigor index, germination, fissure and cracking percentage and seed coat hardness) of dried seeds were analyzed through response surface method. In microwave assisted fluidized bed drying, the effect of air temperature and microwave power levels were studied on the drying kinetics and quality parameters at a constant air velocity of 7 m/s. A face centered central composite design with three levels of each variable was used to generate models for the responses. The study showed that drying under two methods resulted in high germination percentage and low cracking with reduction in the germination time as depicted through vigor index. Also, the seed coat was highly damaged during drying and resulted in fissures and decrease in hardness of the seed coat.

Keywords: Seed drying; Fluidized bed dryer; Microwaves; germination; Seed quality; drying kinetics

Abbreviations

FBD: Fluidized bed dryer

MFBD: Microwave assisted fluidized bed dryer

4.2 Introduction

Seed drying is one of the important post-harvest operations in a seed processing industry. Drying of seeds tends to be different from grains due to distinct quality requirements of the end product. Most of the seeds are either dried in a fixed bed dryer or moving bed dryers such as concurrent, counter-current and cross flow dryers. Fixed bed causes heterogeneity in the quality of the dried end product depending upon the position of the seeds in the bed. However, with moving bed the problem of heterogeneity is solved due to varying position of the dried material during drying. All these methods often come under as low drying rate methods because drying time is usually higher. But these drying methods are accepted globally because the dried seeds are required to have good field emergence and germination when sown.

Felipe and Barrozo (2003) studied the drying of soybean seeds in a concurrent bed dryer and developed empirical equations for various quality attributes like germination, vigor, and fissure after drying. M. Barrozo, Felipe, Sartori, and Freire (2006) studied the drying of soybean in countercurrent and cross current flows moving bed dryers. Fixed bed drying of soybean seeds was carried out by Souza, Miranda, and Barrozo (2015) and the quality of seeds was studied at different positions in a fixed bed. The result showed the sign of non-homogeneity in the quality of soybean seeds at different positions in the bed. A lot of studies concentrate on using higher drying rate dryers for the drying of seeds and maintaining its germination potential. In the case of microwave drying for seeds, continuous operation of the microwaves killed the germination potential of seeds (Łupińska et al., 2009; Nair et al., 2011), but the intermittent operation was able to reduce drying time while maintaining a good quality of seeds (Nair et al., 2011). Fluidization and semi-fluidization at low velocities may result in a decrease of drying time and maintaining homogeneity in the bed as compared to fixed bed without compromising the quality of seeds. Fluidized bed drying have been used for different types of seeds for example soybean (Z. Li, Kobayashi, Nishimura, & Hasatani, 2002), terebinth (Amiri Chayjan & Kaveh, 2014), squash seeds (Chayjan, Salari, Abedi, & Sabziparvar, 2013), turnip seeds (Reyes, Campos, & Vega, 2006), wheat and rice (Jittanit, Srzednicki, & Driscoll, 2013). In the drying of wheat and rice in a fluidized bed and spouted bed dryer by Jittanit et al. (2013), it was concluded that the fluidized bed dryer resulted in higher drying rate but energy consumption was low in spouted bed dryer. In terms of germination percentage, both drying methods were able to produce good germination potential for seeds. For higher temperature, the spouted bed was preferred and for lower temperature fluidized bed was found better. Clemente, Sanjuán, Cárcel, and Mulet (2014) studied the drying of grape seeds in a stationary bed at different air temperatures and air velocity with drying assisted by ultrasound. It was concluded that ultrasound did not affect the drying kinetics of the grape seeds. A combination of fluidized bed and microwave may result in providing higher drying rates and simultaneously solving the problem of heterogeneity in the bed. Establishing these studies and hypothesis, the main purpose of this study is:

1. To study the drying kinetics of soybean in a fixed bed, fluidized bed and microwave assisted fluidized bed.
2. To study seed quality through various seed quality tests and to predict the efficiency of these dryers in seed industries.

4.3 Materials and Methods

4.3.1 Materials

OAC-CALYPSO soybean variety from Quebec, Canada was used for the drying experiments. Seeds initial moisture content was measured by the oven-drying method by putting the seeds in the oven for 72 hours at 105°C (Standard, 2001). The initial moisture content of the soybean seeds came out to be 7.02% (wb). Therefore, the moisture content was increased to 21% through a rewetting process. In a rewetting procedure, 120 g of soybean seeds was taken in a glass container and a calculated amount of water was added to it. The glass containers were then maintained at a temperature of 12°C in a refrigerator for three days to avoid spoilage (Nair et al., 2011). To ensure the uniform absorption of the moisture inside the seeds, containers were shaken twice every day for two days. The average diameter of the soybean seeds was 5.68 mm measured through micrometer.

4.3.2 Fluidized bed drying and microwave assisted-fluidized bed drying

4.3.2.1 Drying Equipment

Fluidized and microwave assisted fluidized bed drying system employed in this study is shown in Figure 4.1. A domestic microwave oven (Panasonic Inc., Canada) was recast for the drying experiments. Microwave oven operated at 2450 MHz and maximum output microwave power of 700 W. The air required for drying and fluidization was provided by the blower (Lesson Electric, Wisconsin, USA). Two 2 kW heaters were used to preheat the air and the PID controller (CN9500, Temperature Controller, Omega, USA) was used to maintain the constant temperature of air for drying. Microwave chamber had cylindrical fluidization column made of glass of dimensions 100 mm in diameter by 300 mm in length. Perforated plates made of polypropylene were placed at the bottom and top of the fluidizing chamber and attached to the wall of the microwave cavity. Humidity and temperature were recorded through humidity sensors (HMP50, Campbell Scientific Inc.) and temperature probes (type K, thermocouple) respectively installed at different points in the system. Dampers were installed to control the airflow velocity and the anemometer (Testo 605i, Testo SE & Co.) was used to measure the airflow velocity. A data acquisition system (Agilent, 34970A) was used to monitor drying.

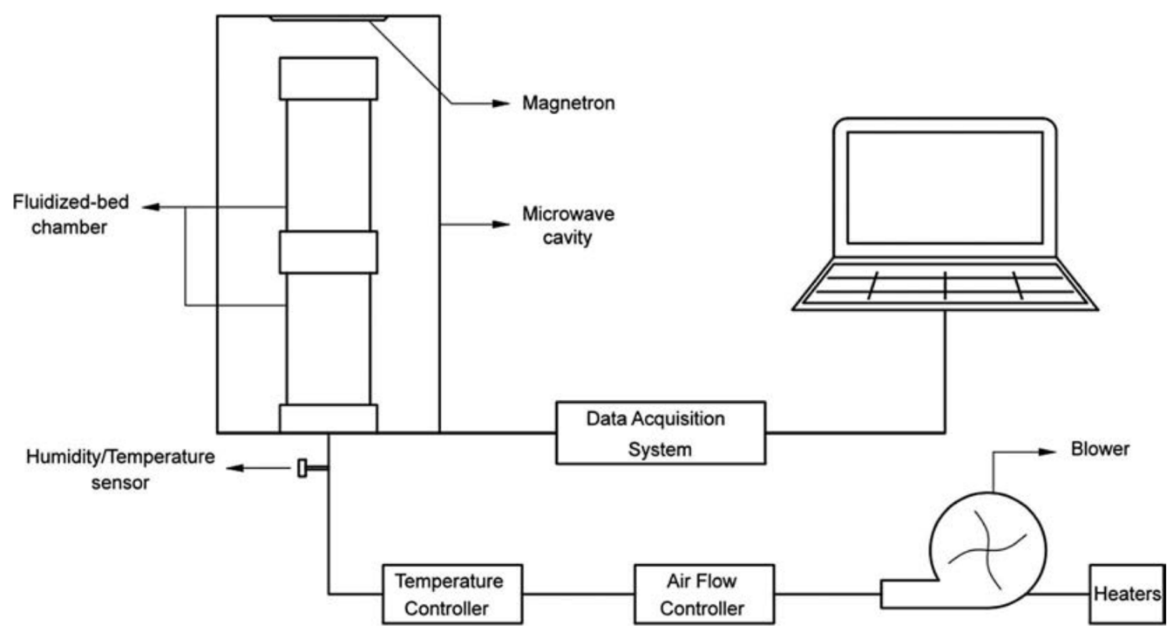


Figure 4.1 Experimental setup for fluidized and microwave assisted fluidized bed drying; Reprint with permission

4.3.2.2 Drying procedure

The drying was carried out by taking 120 g of soybean seeds with 21% (wb) moisture content and drying until the moisture content reaches 11% (wb). The seeds were placed 30 minutes at room temperature before each drying run. The column was periodically weighed over the drying period and in the time interval of weighing, the air velocity was kept running to maintain the constant temperature of the air. Seeds weighing 120 g in the fluidization column resulted in the bed depth of 30 to 33 mm. Before carrying out the experiments, preliminary tests were done to calculate minimum incipient fluidization velocity and fluidization velocity for 120 g seeds. For the fluidized bed drying of soybean seeds, air velocity of 1 (fixed bed), 4 (initial fluidization) and 7 (fluidization) m/s along with the air temperatures of 30, 40 and 50 °C were employed as process variables. For microwave assisted fluidization drying at constant air velocity of 7 m/s, microwave power levels of 0, 2 (150 W) and 4 (300 W) along with air temperatures of 30, 40 and 50 °C were used as process variables. Due to drying system inefficiency, microwaves were reflecting back to the magnetron during microwave assisted fluidized bed drying of soybeans. For this, a glass jar with 50 ml of water was placed in the cavity to absorb reflections, when the moisture content got below 16% during drying.

4.3.2.3 Experimental design

Experiments were designed according to the response surface methodology with two independent variables in each drying method. Air temperature and air velocity were the two independent variables in the case of fluidized bed drying. Air temperature and microwave power level were the two independent variables in the case of microwave assisted fluidized bed drying. Thirteen drying runs were carried out which were designed according to the face centered central composite design with three levels of each. The levels of each variable in the actual and coded form are shown in Table 4.1 and various combinations of the drying run according to the design as mentioned above is shown in Table 4.2. Experiments were randomized and the center point was replicated five times to reduce the variability.

Table 4.1 Levels of independent variables in drying of soybean seeds

Fluidized bed drying				
Variable	Name (unit)	Level		
		-1	0	+1
AT	Air Temperature (°C)	30	40	50
AV	Air velocity (m/s)	1 (fixed)	4 (Incipient-fluidization)	7 (full fluidization)

Microwave assisted fluidized bed drying				
AT	Air Temperature (°C)	30	40	50
PL	Microwave power level	0	2 (~150W)	4 (~300W)

Table 4.2 Face Centered central composite design level combinations

Experiment No.	Variable combination	
	AT	AV/PL
1	-1	-1
2	1	-1
3	-1	1
4	1	1
5	-1	0
6	1	0
7	0	-1
8	0	1
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0

4.3.3 Drying Kinetics

4.3.3.1 Drying time and drying rate

The drying time required to reach the final moisture content of 11% was calculated with the help of Curve Expert Professional® ver. 2.0.3. Different mathematical models were fitted through non-linear regression and the rational function below was used to predict the drying time.

$$\mathrm{MC} = \frac{a+(b\times t)}{1+(c\times t)+(d\times t^2)} \quad \text{……(27)}$$

Where MC is the moisture content in dry basis and t is the drying time in minutes.

Drying rate as a function of drying time was calculated to study how the drying proceeds till the final moisture content is reached. Drying rate was calculated as shown here:

$$Drying\ rate = \frac{Mc_{t+\nabla t} - Mc_t}{t} \qquad \ldots\ldots(28)$$

Where M_c is the moisture content in wet basis at t and t+∇t time in minutes.

4.3.3.2 Mathematical modelling of drying data

In order to determine the mathematical models for describing the drying conditions, two mathematical models were considered for the modelling of the experimental drying data. The Newton model, Eq. (29) and the Page model, Eq. (30) have been used to describe the drying kinetics of various agricultural and food products (Giri & Prasad, 2007; Kardum et al., 2001; Prabhanjan et al., 1995; Sharma & Prasad, 2001). In this study, both the models were tested for their validity in the fluidized bed and the microwave fluidized bed drying of soybean.

$$MR = EXP(-K * t) \qquad \ldots\ldots(29)$$

$$MR = EXP(-k * t^n) \qquad \ldots\ldots(30)$$

MR is moisture ratio which is $(M-M_e) / (M_o-M_e)$, where M is moisture content at any time t in dry basis, M_o is initial moisture content in dry basis, M_e is the equilibrium moisture content in dry basis and t is the drying time in minutes.

The parameters K, k and n were determined through nonlinear regression carried out in SPSS software program. The goodness of fit was determined through the coefficient of determination (R^2), chi-square χ^2, and root mean square error (RMSE). The highest value of R^2 and lowest value for χ^2 and RMSE best describes the drying conditions.

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp} - MR_{pre}\right)^2}{N - z} \qquad \ldots\ldots.(31)$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{n}\left(MR_{exp} - MR_{pre}\right)^2\right)^{0.5} \qquad \ldots\ldots.(32)$$

Where MR_{pre} is predicted moisture ratio, MR_{exp} is experimental moisture ratio, N is the number of observations and Z is the constants in the drying model.

4.3.3.3 Mass transfer diffusivity calculation

When the material is dried, the drying rate can be constant, or it can vary with the time. During constant drying rate period, the surface is holding moisture and the drying rate is dependent on the rate of evaporation of water. In falling rate drying period, there is a movement of moisture from inside of the sample with the help of diffusion. Moisture diffusivity was calculated with the help of Fick's law of diffusion (Dadalı et al., 2007; Ranjbaran & Zare, 2012) :

$$\frac{\partial M}{\partial t} = \nabla^2 (D_{eff} M) \qquad \text{.......(33)}$$

where M is the moisture content, t is the drying time (s) and D_{eff} is the effective moisture diffusivity (m^2/s). Considering the spherical coordinates and constant value of D_{eff}, the following equation can be rewritten as:

$$\frac{\partial M}{\partial t} = \left(D_{eff} \frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right) \qquad \text{.......(34)}$$

where r is the radius of the seed kernel (m).

The theoretical solution of the above equation is shown in Eqn. (35) and it has been used by several researchers for the calculation of effective moisture diffusivity in the drying of the agricultural products (Jayatunga & Amarasinghe, 2019).

$$MR = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-D_{eff}\, n^2 \Pi^2}{r^2} t\right) \qquad \text{....... (35)}$$

The above equation will be reduced to the first term of the series and researchers have claimed that this reduction doesn't have a significant effect on the prediction of diffusivity value (Doymaz & Pala, 2003).

$$MR = \frac{6}{\pi^2} \exp\left(\frac{-D_{eff} \pi^2}{r^2}\ t\right) \qquad \text{.......(36)}$$

Eqn. 6 was evaluated for Fourier number, $F_o = D_{eff} * t/r^2$ for diffusion and can be rewritten as

$$\ln MR = \ln\left(\frac{6}{\pi^2}\right) - F_o\, \pi^2 \qquad \text{.......(37)}$$

For π = 3.14, the Eqn. 7 takes the following form

$$F_0 = -0.0504 - 0.1014 \ln MR \qquad \text{.......(38)}$$

where, $F_o = D_{eff} * t/r^2$ and

$$D_{eff} = \frac{F_o r^2}{t} \quad \text{.......(39)}$$

Effective moisture diffusivity was calculated by substituting the positive values of F_o (calculated through Eqn. 39) and drying time corresponding to each moisture ratio along with the radius of soybean kernel (Dadalı et al., 2007). The average effective moisture diffusivity was calculated by taking the average of diffusivity values at different times.

4.3.4 Seed quality

4.3.4.1 Germination test

High germination potential is one of the most important properties required for the seed grade soybean. At a laboratory scale, the test was carried out by rolled paper towel method in which fifty seeds were placed on the paper moistened with distilled water according to water: paper weight ratio of 2.5:1. The wet paper along with seeds is then placed in a germinator at 25°C in an upright position in a jar for eight days for soybeans. Since paper towels occasionally get dried and jars were filled with distilled water up to 3 cm from the bottom to keep them moistened. On the 8^{th} day, percentage of seeds germinated or normal seedlings were counted and the germination rate was expressed as a number of seeds germinated to the total seeds placed (Reddy et al., 1998).

4.3.4.2 Seedling Vigor index

It is seen that seeds tend to circulate reserves from storage tissues to embryo more efficiently in vigorous seeds as compared to non-vigorous seeds. Damaged seeds have slow germination which means that the time for water uptake is increased reading to slower primary root development (Marcos Filho, 2015). Ten normal seedlings from the germination test were taken and their shoot and radicle length were measured by the ruler in cm (Sheidaei et al., 2014). Seedling vigor index was calculated according to the following relation:

Seedling vigor index= (Mean of radicle length + Mean of shoot length) × final germination percent

4.3.4.3 Seed Fissures and cotyledon cracking test

The Sodium Hypochlorite test was used to find the non-fissured seeds with healthy seed coat after drying treatment. Seeds after drying were submerged in a 5% solution of sodium hypochlorite. After 7 minutes, the number of swollen and fissured seeds were calculated and fissure index was expressed in terms of percentage (Felipe & Barrozo, 2003).

Cracking in the cotyledons was calculated by visually inspecting seeds with the fluorescent light and the cracking percentage was calculated as:

$$Cracking\ percentage = \frac{m_c}{m_s} \times 100 \quad \ldots\ldots(40)$$

Where m_c is the mass of cracked seeds and m_s is the total mass of the kernels in g

4.3.4.4 Seed coat penetration test

Seed coat helps in the protection of seeds under adverse environmental conditions. It also protects the embryo and provides a barrier against the microbial infection. Seed coat hardness tends to have a negative correlation with cracking in the soybean seeds. Also, hard seeds provide protection against fluctuations in temperature as well as humidity (Mohamed-Yasseen, Barringer, Splittstoesser, & Costanza, 1994; Senda et al., 2017).

Effect of drying on the hardness of the seed coat was studied with the help of seed coat penetration test. The seed was horizontally sliced into two part with a razor blade and the coat was peeled off up to 1 cm in width. A Universal Testing Machine (Instron–4502, Instron Corporation, USA) equipped with a Kramer shear press and a cylindrical probe (diameter: 1.5 mm) was used to shear the seed coat. Seed coat extracted from the seed was placed on the disc with 2 mm hole at the center. The force required to break the load was recorded with the help of computer software (Instron series IX, version 8.25).

4.4 Result and Discussions

4.4.1 Drying kinetics

4.4.1.1 Effect of Air Temperature

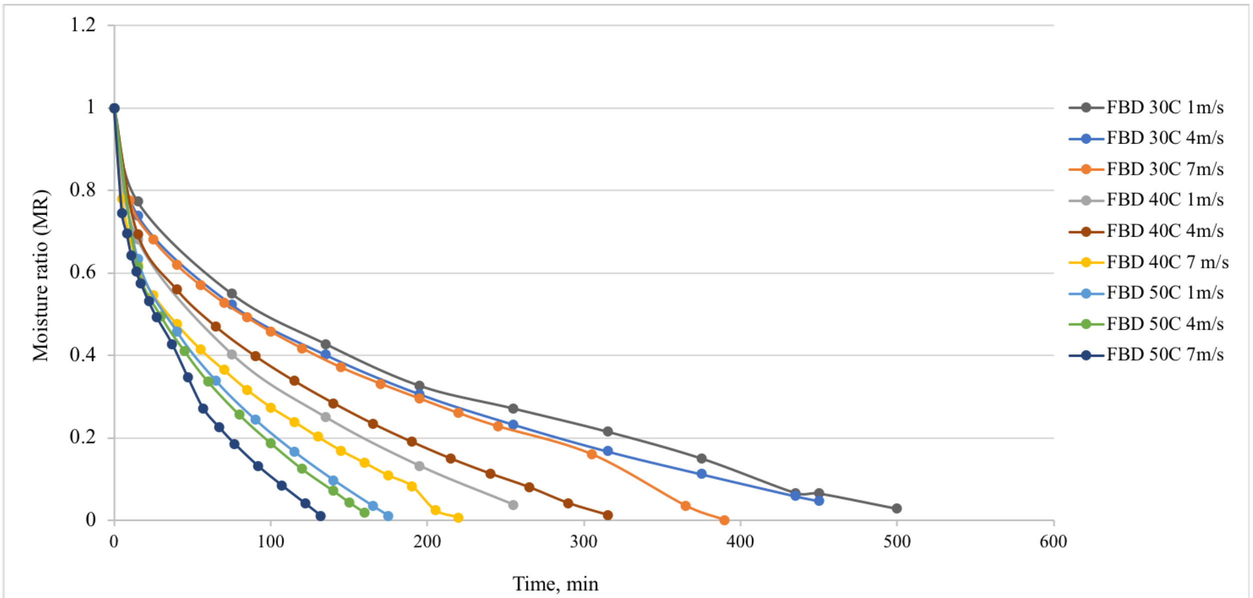
For fluidized bed drying and microwave assisted fluidized bed drying of soybean, an increase in air temperature resulted in a decrease of drying time as shown in Figure 4.2 (a) and Figure 4.2 (b). With increasing air temperature, more energy was supplied which resulted in a higher drying rates. Similar results have been reported by Chayjan et al. (2013) and Jittanit et al. (2013) for squash and wheat seeds respectively. From the ANOVA shown in Table 4.3 and 4.4, it is seen that air temperature effect was significant at 1% for both fluidized and microwave assisted fluidized bed drying of soybeans. However, the air temperature had a larger influence in the case of fluidized bed dryer than microwave assisted fluidized bed dryer as depicted by higher F values.

4.4.1.2 Effect of Air Velocity

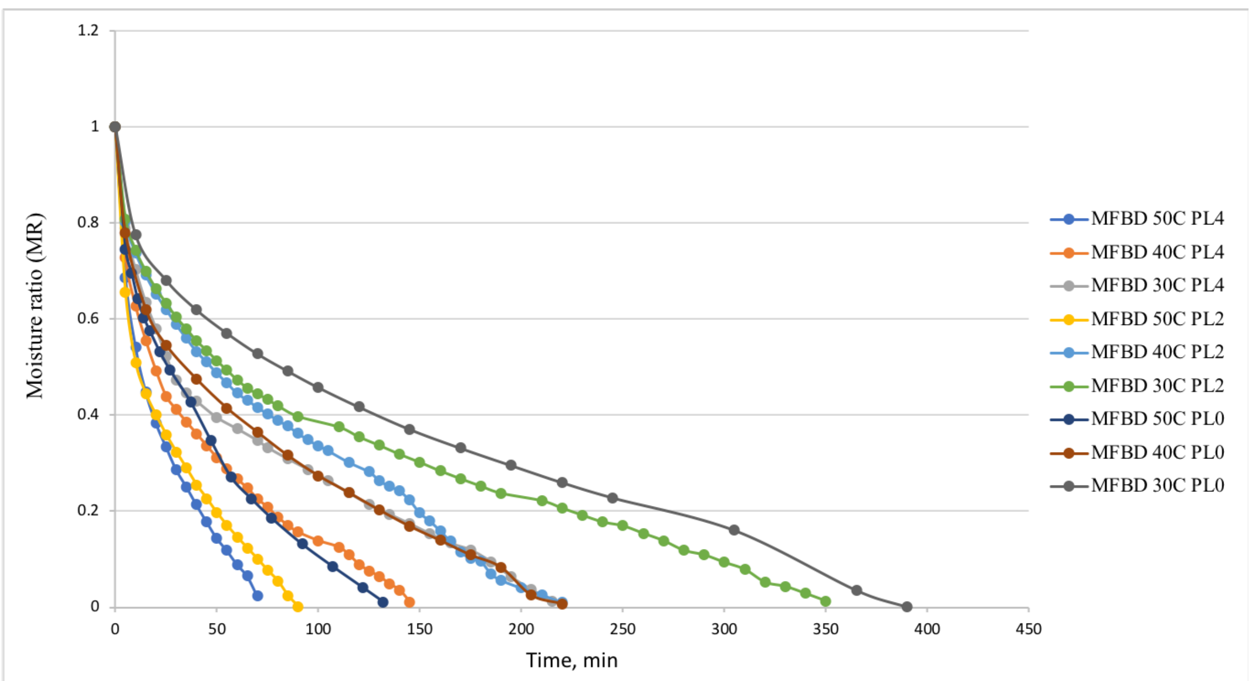
During fluidized bed drying, increase in air velocity resulted in a decrease in the drying time. However, a small influence can be seen when the velocity shifted from 1(fixed bed) to 4 (incipient fluidization) m/s than from 1 (fixed bed) to 7 (full fluidization) m/s. The air velocity was having a small effect on the drying time because the work was carried out in a shallow bed of height 30 to 32 mm and also, air velocity for fluidization was kept low to minimize the injury due to impact. From the ANOVA shown in Table 4.3, it can be seen that air velocity did have a significant effect on drying time, but the effect was low as previously discussed.

4.4.1.3 Effect of Microwaves

From Figure 4.2 (b) it can be seen that the introduction of microwaves at a constant velocity of 7 m/s resulted in a decrease of drying time at different temperatures. This can be attributed to the fact that constant fluidization of the particles proved to increase the probability of the particles to be impacted by the microwaves and hence resulted in a higher rate of evaporation. A similar result has been reported by Reyes et al. (2006) for turnip seeds drying in the microwave fluidized bed dryer. However, power level 2 had a lower influence on the drying time than power level 4 at all drying temperatures. This can be explained as the seeds are the low moisture commodities and the effect of microwaves decrease with a decrease in moisture content and microwave power. From Table 5.4, it can be seen that microwave had a significant effect on drying time, but the significance was less as compared to air temperature in the microwave assisted fluidized bed drying.



(a)



(b)

Figure 4.2 Drying curves for (a) FBD and (b) MFBD

Table 4.3 ANOVA showing the linear, quadratic and cross product effect of the process variables on study parameters in fluidized bed drying

Source of Variation	df	Drying Time		Germination Percentage		Fissure Percentage		Vigour Index	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Model	5	36136.27	268.41*	18.21	9.8*	705.03	120.85*	37140.13	10.48*
AT	1	1.64E05	1223.3*	64.29	34.6*	112.67	19.31*	1.65E+05	46.51*
AV	1	10787.41	80.13*	18.48	9.95**	2320.67	397.77*	17397.86	4.91
AT^2	1	3880.64	28.82*	0.0454	0.0245	1.59	0.2724	3054.79	0.8619
AV^2	1	1364.96	10.14**	2.27	1.22	919.02	157.52*	379.23	0.1073
AT*AV	1	1109.89	8.24**	5.88	3.16	49	8.4**	413.31	0.1166
Residual	7	134.63		1.86		5.83		3544.19	
Lack of Fit	3	53.03	0.2708	0.7283	0.8452	3.21	0.4119	2019.62	0.4308
Pure Error	4	195.83	2.71			7.8		4687.62	
Total	12								

df-Degree of freedom; MS-Mean square; AT-Air temperature; AV-Air velocity
* Significant at 1%.
** Significant at 5%.

Contd.

Source of Variation	df	Drying constant (k)		Drying constant (K)		Diffusivity		Cracking Percentage		Seed coat hardness	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Model	5	0.0003	15.76*	0.0001	95.95*	52.42	62.94*	13.16	24.06*	0.8396	0.6078
AT	1	0.0007	32.99*	0.0003	396.82*	249.62	299.7*	11.15	20.39*	0.0046	0.0041
AV	1	0.0008	38.31*	0	36.08*	2.41	2.89	45.32	82.85*	3.03	2.73
AT^2	1	0	1.91	6.8E-06	8.39**	2.62	3.14	0.3781	0.6912	0.2056	0.1852
AV^2	1	0.0001	5.9*	9.6E-06	11.75**	3.49	4.19	5.93	10.84	0.0318	0.0287
AT*AV	1	0	1.34	0	14.43*	0.25	0.3002	0.6162	1.13	0.8118	0.7313
Residual	7	0		8.2E-07		0.8329		0.547		1.11	
Lack of Fit	3	0	6.82**	1.3E-06	3.24	1.05	1.58	0.7216	1.73	0.6042	0.4056
Pure Error	4			4.2E-07		0.6667		0.4161		1.49	
Total	12										

Table 4.4 ANOVA showing the linear, quadratic and cross product effect of the process variables on study parameters in microwave assisted fluidized bed drying

Source of Variation	**df**	**Drying Time**		**Germination Percentage**		**Fissure Percentage**		**Vigour Index**	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Model	5	23474.13	78.5*	5.08	5.7**	491.31	77.23*	18667.13	13.04*
AT	1	94931.2	317.47*	16.63	18.66*	170.67	26.83*	61667.43	43.09*
PL	1	16196.97	54.17*	1.24	1.39	2128.17	334.55*	26400.67	18.45*
AT^2	1	913.14	3.05	6.95	7.82	1.19	0.1864	8.29	0.0058
PL^2	1	2156.38	7.21**	2.62	2.93	129.4	20.34*	4036.1	2.82
AT*PL	1	3902.5	13.05*	0.119	0.1335	16	2.52	699.6	0.4888
Residual	7	299.02		0.8915		6.36		1431.13	
Lack of Fit	3	694.24	265.7*	0.4723	0.3916	4.58	0.5943	1610.12	1.24
Pure Error	4	2.61		1.21		7.7		1296.89	
Total	12								

df-Degree of freedom; MS-Mean square; AT-Air temperature; AV-Air velocity
* Significant at 1%.
** Significant at 5%.

Contd.

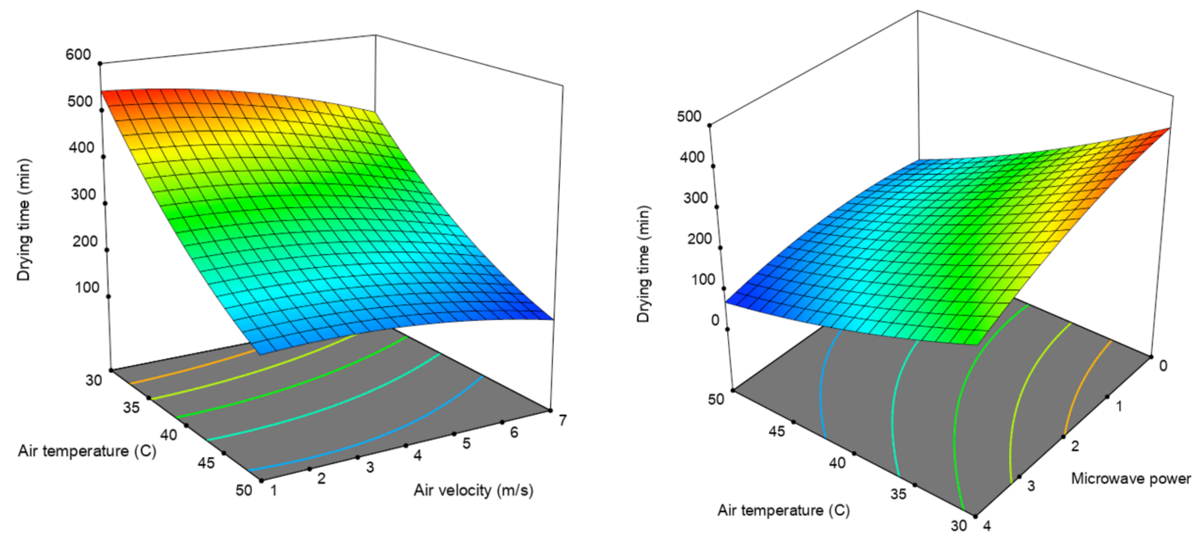
Source of Variation	df	Drying constant (k)		Drying constant (K)		Diffusivity		Cracking Percentage		Seed coat hardness	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Model	5	0.0017	9.07*	0.0003	35.89*	2.34E-20	9.78*	30.2	56.27*	5.3	34.09*
AT	1	0.0041	22.18*	0.001	114.98*	8.23E-20	34.43*	57.35	106.87*	0.1267	0.8151
PL	1	0.0031	17.11*	0.0002	27.66*	2E-20	8.39**	70.73	131.8*	16.89	108.63*
AT^2	1	0.0007	3.94	0.0002	20.62*	8.16E-21	3.41	0.1264	0.2356	0.4083	2.63
PL^2	1	0	0.20	0	2.9	2.6E-25	0.0001	16.16	30.12**	9	57.88*
AT*PL	1	0.0001	0.3971	0	2.39	4.97E-21	2.08	2.59	4.83	0.1875	1.21
Residual	7	0.0002		8.6E-06		2.4E-21		0.5366		0.1555	
Lack of Fit	3	0.0004	339.99*	0	90.93*	2.9E-21	1.48	0.6481	1.43	0.3264	11.97**
Pure Error	4	1.2E-06		2.1E-07		1.98E-21		0.4530		0.0273	
Total	12										

Table 4.5 Regression analysis models for different responses during drying of soybean seeds

Response	**Drying method**	**Second order polynomial regression model**	**R^2**
Drying Time	FBD	$1671.23 - (48.77 \times AT) - (16.58 \times AV) + (0.55 \times AT \times AV) + (0.37 \times AT^2) - (2.47 \times AV^2)$	0.9948
	MFBD	$1170.15 - (30.2 \times AT) - (60.5 \times PL) + (1.56 \times AT \times PL) + (0.18 \times AT^2) - (6.98 \times PL^2)$©	0.9825
Germination Percentage	FBD	$89.94 - (0.268 \times AT) + (1.83 \times AV) - (0.04 \times AT \times AV) + (0.0012 \times AT^2) - (0.1 \times AV^2)$	0.875
	MFBD	$110.37 - (1.41 \times AT) + (1.09 \times PL) - (0.008 \times AT \times AV) + (0.015 \times AT^2) - (0.24 \times PL^2)$	0.8027
Fissure Percentage	FBD	$11.89 - (0.64 \times AT) + (18.1 \times AV) + (0.1167 \times AT \times AV) + (0.007 \times AT^2) - (2.02 \times AV^2)$	0.9885
	MFBD	$39.71 + (0.21 \times AT) + (20.26 \times PL) - (0.1 \times AT \times PL) + (0.006 \times AT^2) - (1.71 \times PL^2)$	0.9622
Vigor Index	FBD	$2281.22 - (41.8 \times AT) + (6.01 \times AV) - (0.33 \times AT \times AV) + (0.3325 \times AT^2) - (1.3 \times AV^2)$	0.8821
	MFBD	$1556.18 - (12.8 \times AT) - (21.3 \times PL) + (0.66 \times AT \times PL) + (0.017 \times AT^2) - (9.55 \times PL^2)$	0.9031
Drying constant (K)	FBD	$0.016 - (0.0007 \times AT) - (0.0032 \times AV) + (0.00005 \times AT \times AV) + (0.000016 \times AT^2) + (0.0002 \times AV^{2)}$	0.9856
	MFBD	$0.0969 - (0.0053 \times AT) - (0.0044 \times PL) + (0.00011 \times AT \times PL) + (0.00008 \times AT^2) + (0.00075 \times PL^2)$	0.9625
Drying constant (k)	FBD	$-0.05 + (0.0037 \times AT) - (0.0056 \times AV) + (0.00008 \times AT \times AV) - (0.000038 \times AT^2) + (0.000744 \times AV^2)$©	0.9184
	MFBD	$0.21 - (0.01 \times AT) - (0.00073 \times PL) + (0.000213 \times AT \times PL) + (0.00016 \times AT^2) + (0.00091 \times PL^2)$	0.8662

Diffusivity	FBD	$(2.6E-12)-(1E-12\times AT)-(4.54E-12\times AV)-(8.3E-14\times AT\times AV)+(9.7E-14\times AT^2)+(1.24E-12\times AV^2)$	0.9782
	MFBD	$(6.36E-10)-(3.5E-11\times AT)-(4.18E-11\times PL)+(1.76E-12\times AT\times PL)+(5.4E-13\times AT^2)+(7.67E-14\times PL^2)$	0.8748
Cracking Percentage	FBD	$6.58-(0.212\times AT)-(0.909\times AV)+(0.013\times AT\times AV)+(0.0037\times AT^2)+(0.162\times AV^2)$	0.945
	MFBD	$3.15-(0.057\times AT)-(2.31\times PL)+(0.04\times AT\times PL)+(0.0021\times AT^2)+(0.604\times PL^2)$	0.9757

AT-Air Temperature; AV-Air Velocity; PL-Microwave power Level
©Lack of fit significant



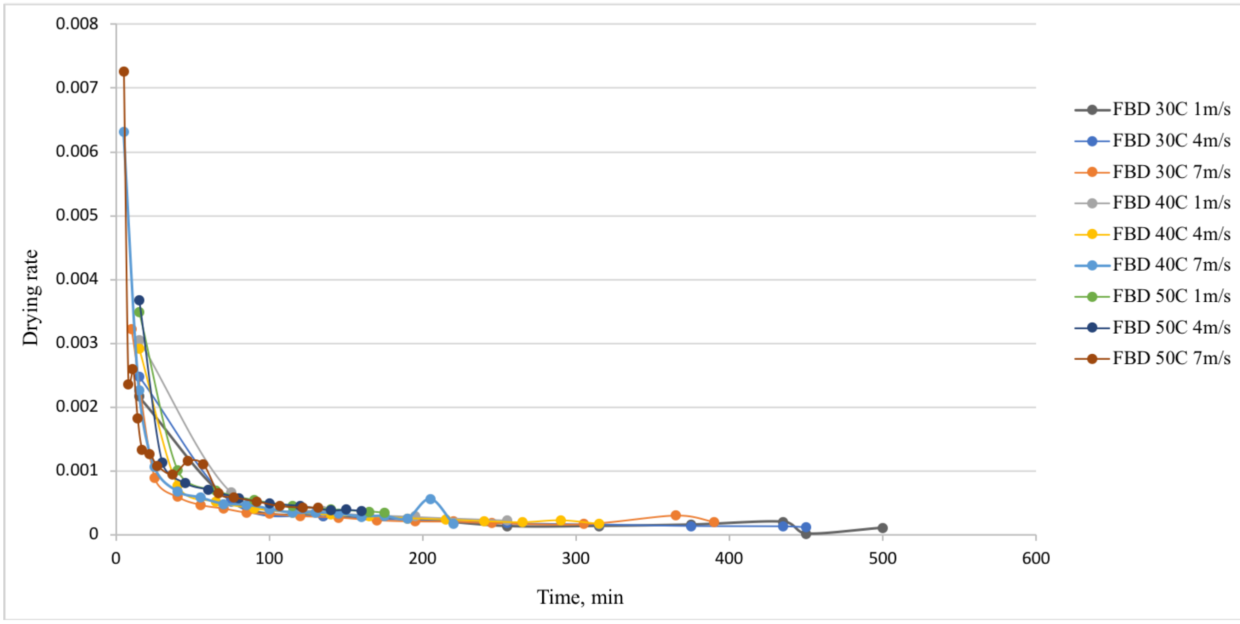
(a) (b)

Figure 4.3 Drying time response chart for (a) FBD and (b) MFBD

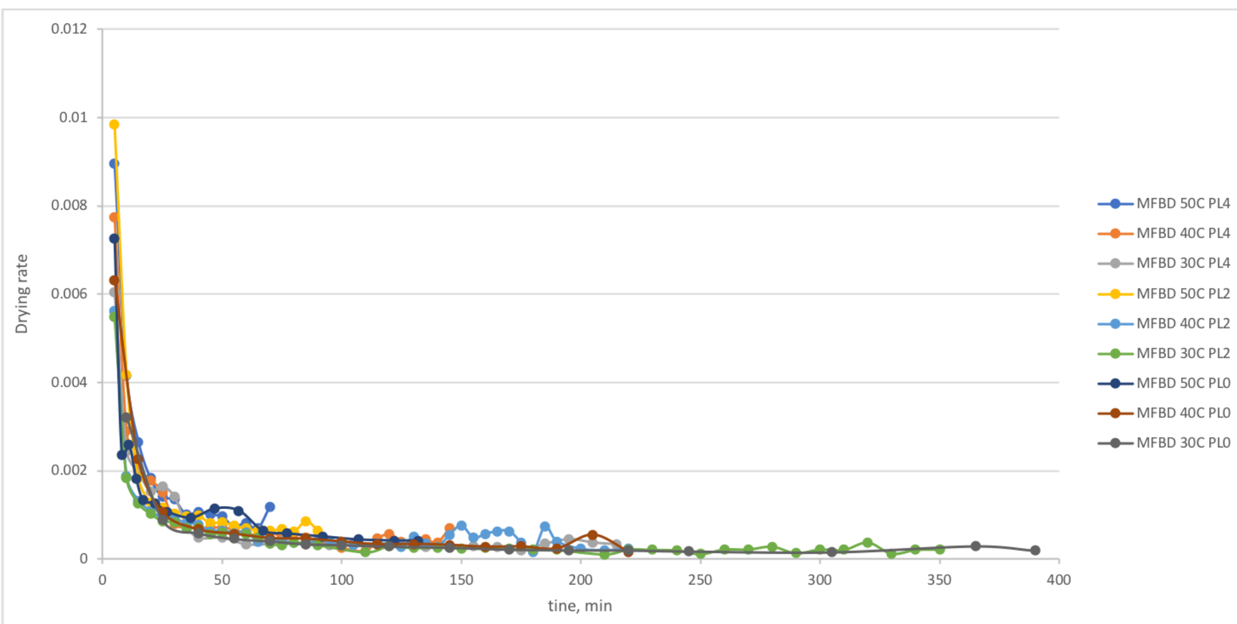
4.4.1.4 Drying rate

Drying curves as shown in Figure 4.4 (a) and 4.4 (b) proved that for all drying treatments in fluidized bed drying and microwave assisted fluidized bed drying, drying took place in the falling rate period. Drying rates were higher in the case of microwave fluidization than convective fluidization. From the figures, it can also be inferred that drying rates were approximately similar in the later stages of drying.

Effect of process variables on drying time in the case of fluidized and microwave assisted fluidized bed drying is shown in Figure 4.3. The second order polynomial correlating drying time with process variables in two drying methods is shown in Table 4.5. A lack of fit was significant in the case of microwave assisted fluidization and this shows that the given model will not predict the experimental conditions well.



(a)



(b)

Figure 4.4 Drying rate curves for (a) FBD and (b) MFBD

4.4.2 Mathematical Modelling

The mathematical modelling of the experimental data fitted to an exponential and page model showed a good fit as depicted by R^2, χ^2 and RMSE values presented in Table 4.6. The drying rate constant increase with an increase in air temperature, air velocity and microwave power levels in both the drying methods. High values of R^2 and low values of χ^2 and RMSE showed that these models explain the drying conditions effectively. The analysis of variance of drying rate constants K and k obtained through exponential and page model respectively is shown in Table 4.3 and 4.4. For fluidized bed drying, air temperature and air velocity had a significant effect on both constants from the two models. However, in the page model, air velocity had a more significant effect on drying constant, unlike the exponential model where the air temperature was the dominant factor. For microwave assisted fluidized bed drying, both air temperature and microwave power level had a significant effect on constants with air temperature more significant than microwave power level. The second order polynomial models for the drying constants showed a major lack of fit and this infers that the models listed in Table 4.5 may not be efficient in predicting drying constants. The response plot for both drying constants in FBD and MFBD is shown in Figure 4.5.

Table 4.6 Mathematical modelling parameters calculated through regression analysis

Fluidized Bed Drying										
Air Temperature (°C)	**Air Velocity (m/s) / Microwave power level**	**Exponential Model**				**Page Model**				
		K (min^{-1})	**R^2**	**χ^2**	**RMSE**	**k (min^{-1})**	**n**	**R^2**	**χ^2**	**RMSE**
30	1	0.00594	0.9838	0.003786	0.058667	0.025	0.736	0.984	0.0017801	0.0381639
40	1	0.012	0.9836	0.005596	0.068289	0.036	0.766	0.989	0.0018042	0.0346816
50	1	0.018	0.9871	0.002943	0.051148	0.045	0.79	0.986	0.0016711	0.0360523
30	4	0.00662	0.9812	0.004541	0.063929	0.034	0.69	0.986	0.0051087	0.0639297
40	4	0.01114	0.981	0.003915	0.060301	0.042	0.720	0.983	0.0015011	0.0358705
50	4	0.0198	0.986	0.002772	0.050204	0.049	0.783	0.986	0.0013263	0.0329419
30	7	0.00766	0.976	0.006118	0.075886	0.039	0.69	0.968	0.0015054	0.0347036
40	7	0.015	0.968	0.006244	0.076662	0.068	0.659	0.979	0.0016728	0.0384191
50	7	0.0266	0.983	0.004437	0.064627	0.069	0.738	0.984	0.0013170	0.0340896
Microwave fluidized bed drying										
30	0	0.00766	0.976	0.006118	0.075886	0.039	0.69	0.968	0.0015054	0.0347036
40	0	0.015	0.968	0.006244	0.076662	0.068	0.659	0.979	0.0016728	0.0384191
50	0	0.0266	0.983	0.004437	0.064627	0.069	0.738	0.984	0.0013170	0.0340896
30	2	0.01	0.859	0.007804	0.087286	0.057	0.627	0.979	0.0011791	0.0335114
40	2	0.013	0.921	0.004362	0.065216	0.064	0.649	0.961	0.0022004	0.0457215
50	2	0.04	0.917	0.005025	0.068997	0.128	0.668	0.982	0.0011867	0.0325855
30	4	0.017	0.865	0.007979	0.087658	0.083	0.619	0.983	0.0010631	0.0313750
40	4	0.025	0.914	0.004615	0.066710	0.092	0.667	0.988	0.3168137	0.5423874
50	4	0.045	0.962	0.002660	0.049831	0.134	0.848	0.992	0.0005759	0.0223411

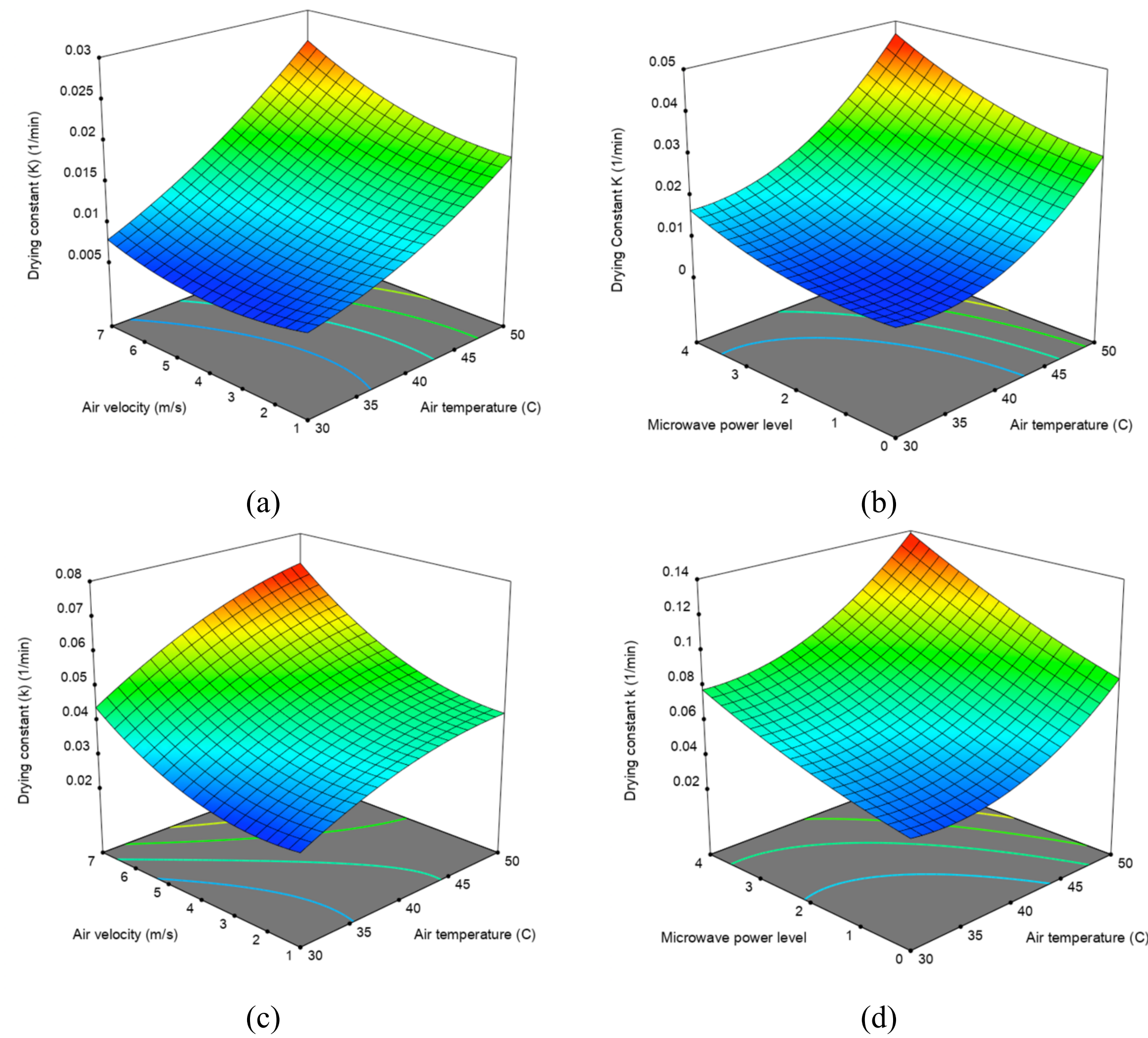
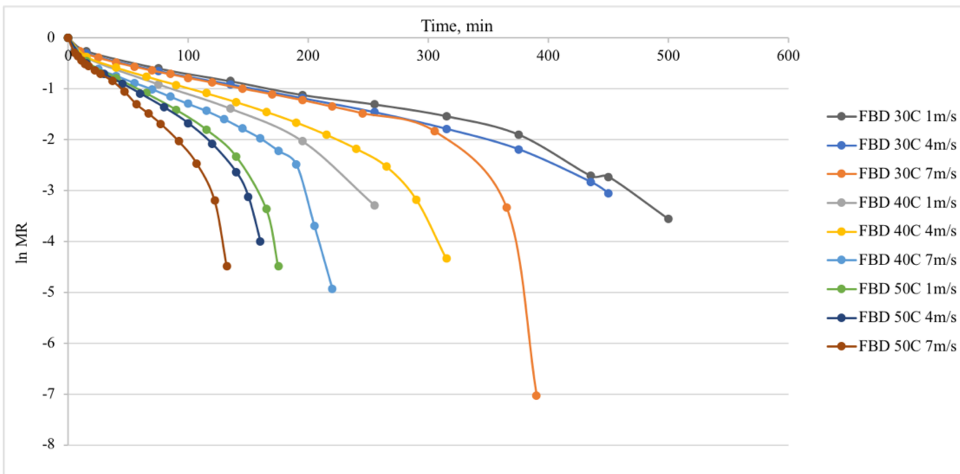


Figure 4.5 Rate constant values from the exponential model in (a) FBD and (b) MFBD; Page model in (c) FBD and (d) MFBD

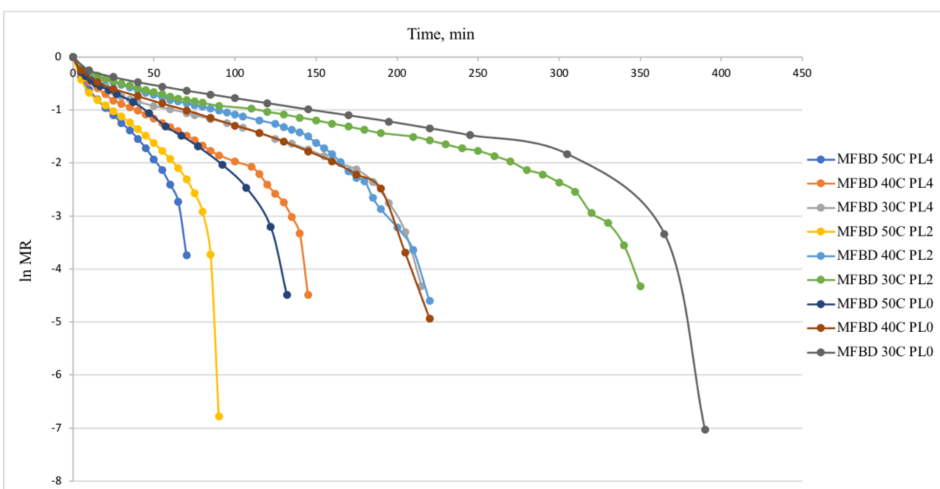
4.4.3 Effective moisture diffusivity and mass transfer calculations

Values of ln MR were plotted against drying time for all drying treatments and is shown in Figure 4.6 (a) and 4.6 (b). From the plot, it can be seen that the drying process was implemented as liquid diffusion in the initial stages of drying and vapor diffusion in the later stages. The same phenomenon was reported in microwave assisted convective drying of soybean seeds. This non-linearity in the figures are due to shrinkage associated with the dried product, non-uniform initial moisture distribution, change in the temperature of the product or variation in the moisture diffusivity along with the moisture content (Sharma & Prasad, 2004). A following second order polynomial was used to correlate ln MR with time and the coefficients of the equation (A, B and C) are shown in Table 4.7.

$$\ln MR = (A \times t^2) + (B \times t) + C \qquad \text{……(41)}$$



(a)

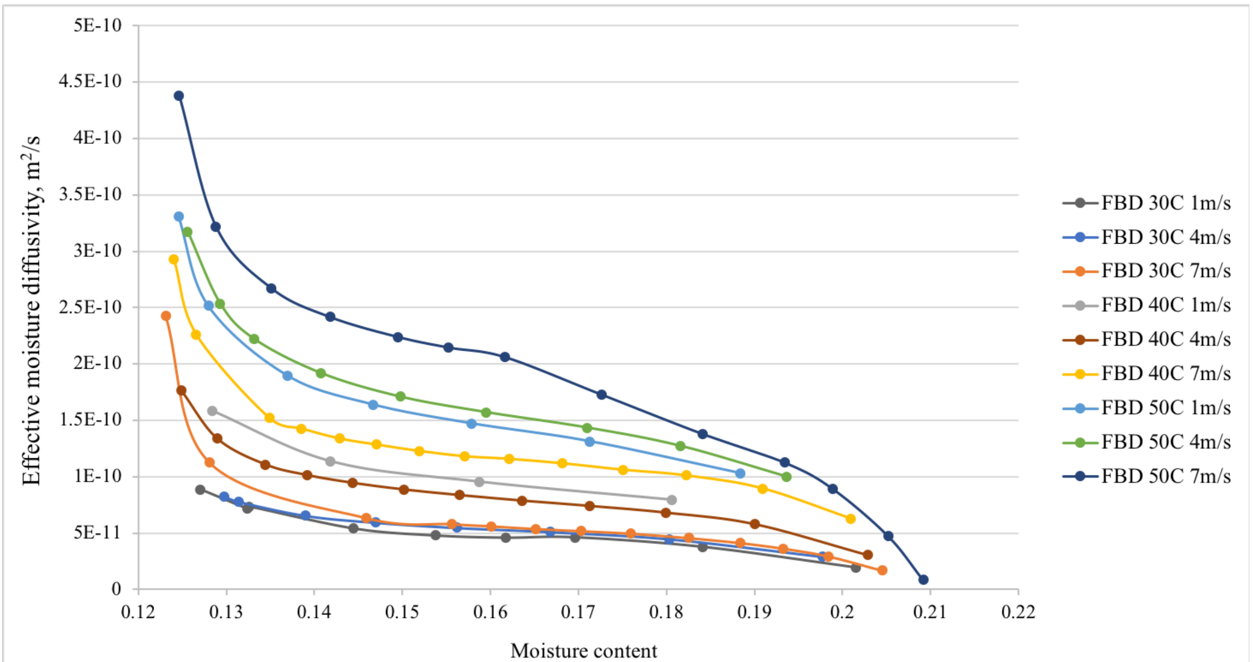


(b)

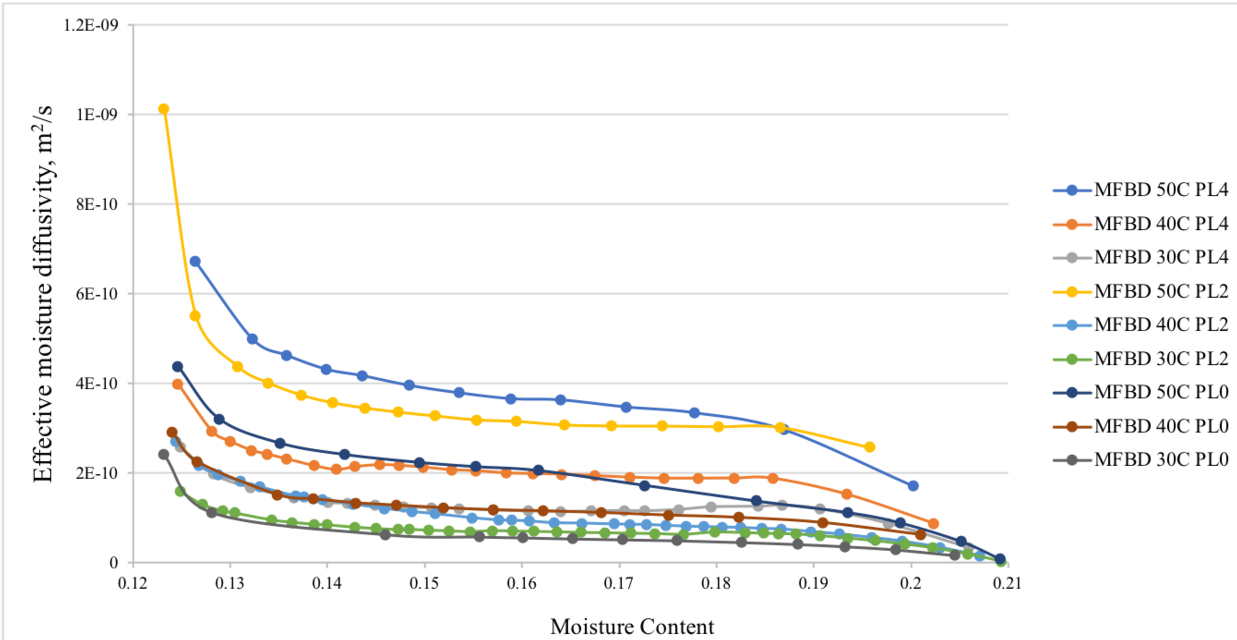
Figure 4.6 Logarithmic of moisture ratio versus time for (a) FBD and (b) MFBD

Figures 4.7 (a) and 4.7 (b) shows the variation of moisture diffusivity along with the moisture content throughout drying. It is noted that for all drying treatments moisture diffusivity increases with a decrease in moisture content. This could be due to an increase in permeability to vapors in later stages of drying. A second order polynomial showing the variation of diffusivity along the moisture content was determined as follows and the values of the coefficients are shown in Table 5.8.

$$D_{eff} = (A \times M^3) + (B \times M^2) + (C \times M) + D \qquad \text{......(42)}$$



(a)



(b)

Figure 4.7 Moisture diffusivity as a function of moisture content in (a) FBD and (b) MFBD

Table 4.7 Regression coefficients and coefficient of determination value at different treatments

Fluidized bed drying						Microwave assisted fluidized bed drying					
Air velocity (m/s)	Air Temperature (° C)	Regression coefficient				Microwave power level	Air Temperature (° C)	Regression coefficient			
		A	B	C	R^2			A	B	C	R^2
1	30	-8E-08	-0.0021	-0.2304	0.9753	0	30	-5E-05	0.0064	-0.6068	0.834
1	40	-2E-05	-0.0062	-0.1676	0.9844	0	40	-8E-05	0.0015	0.4478	0.9192
1	50	-0.0001	-0.0018	-0.2939	0.9591	0	50	-0.0002	-0.0056	-0.3233	0.968
4	30	-5E-06	-0.0039	-0.1888	0.987	2	30	-2E-05	-0.001	-0.4646	0.9382
4	40	-3E-05	-0.0016	-0.3481	0.9575	2	40	-8E-05	0.0036	-0.5006	0.9469
4	50	-9E-05	-0.0056	-0.2904	0.9672	2	50	-7E-04	0.019	-0.7081	0.8226
7	30	-5E-06	0.0064	-0.6068	0.834	4	30	-5E-05	-0.0024	-0.4594	0.9236
7	40	-8E-05	0.0015	-0.4478	0.9192	4	40	-9E-05	-0.0082	-0.4182	0.9335
7	50	-0.0002	-0.0056	-0.3233	0.968	4	50	-3E-04	-0.0191	-0.287	0.9578

Table 4.8 Regression coefficients and coefficient of determination value at different treatments

Fluidized bed drying							Microwave assisted fluidized bed drying						
Air velocity (m/s)	Air Temperature (°C)	Regression coefficient					Microwave power level	Air Temperature (°C)	Regression coefficient			
		A	B	C	D	R^2			A	B	C	D	R^2
1	30	-6E-07	3E-07	-5E-08	3E-09	0.996	0	30	-2E-06	8E-07	-1E-07	8E-09	0.901
1	40	-1E-06	6E-07	-1E-07	6E-09	1	0	40	-2E-06	1E-06	-2E-07	9E-09	0.958
1	50	-3E-06	1E-06	-2E-07	1E-08	0.973	0	50	-2E-06	1E-06	2E-07	1E-08	0.975
4	30	-4E-07	2E-07	-3E-08	2E-09	0.998	2	30	-1E-06	5E-07	-9E-08	5E-09	0.982
4	40	-1E-06	5E-07	-9E-08	5E-09	0.974	2	40	-1E-06	7E-07	-1E-07	7E-09	0.988
4	50	-2E-06	1E-06	2E-07	1E-08	0.980	2	50	-9E-06	4E-06	-7E-07	4E-08	0.823
7	30	-2E-06	8E-07	-1E-07	8E-09	0.901	4	30	-2E-06	1E-06	-2E-07	1E-08	0.968
7	40	-2E-06	1E-06	-2E-07	9E-09	0.958	4	40	-3E-06	1E-06	-2E-07	1E-08	0.916
7	50	-2E-06	1E-06	2E-07	1E-08	0.975	4	50	-4E-06	2E-06	-4E-07	2E-08	0.988

Figure 4.8 shows the values of average effective moisture diffusivity at different treatments in fluidized and microwave assisted fluidized bed drying of soybean. It should be noted that the values of moisture diffusivity were approximately similar for all the treatments except for power levels 2 and 4 at 50 °C. Also, in fluidized bed drying, the effect of air velocity was not prominent at all temperatures. However, the temperature did have a significant effect on the diffusivity. For microwave assisted fluidized bed drying, microwave power level 2 didn't had a significant effect on diffusivity at 30 and 40 °C but power level 4 had much more prominent effect on the diffusivity. Highest moisture diffusivity was recorded at 50 °C and power level 4. The value of average effective moisture diffusivity was found in good agreement for food materials having diffusivity in the range of 10^{-11} to 10^{-9} m^2/s.

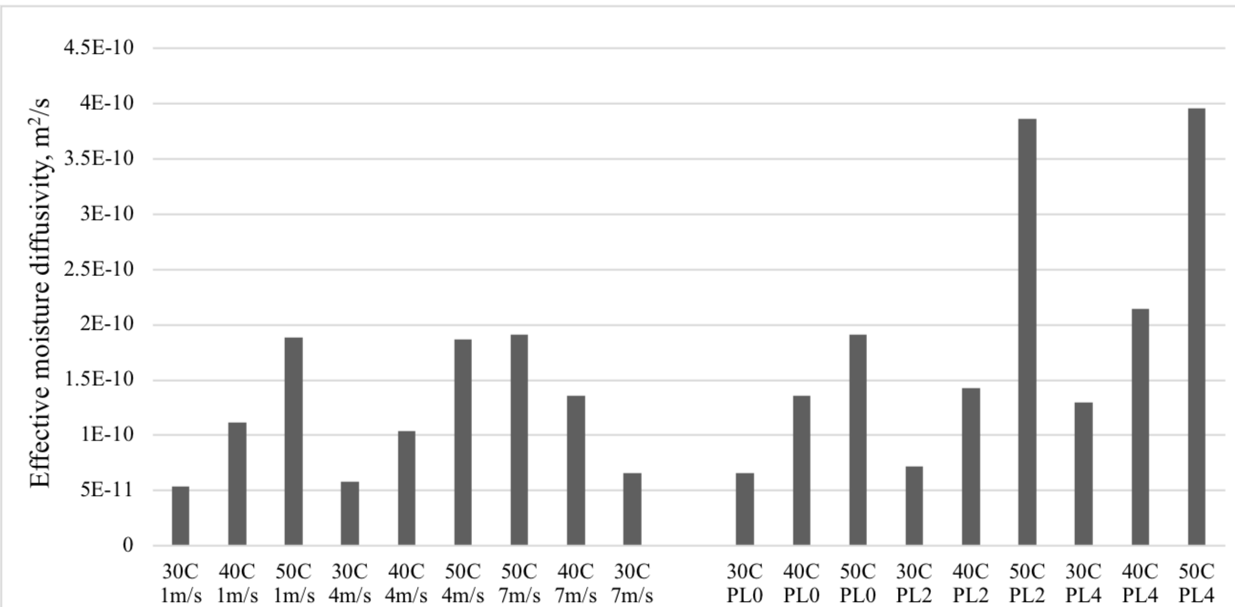
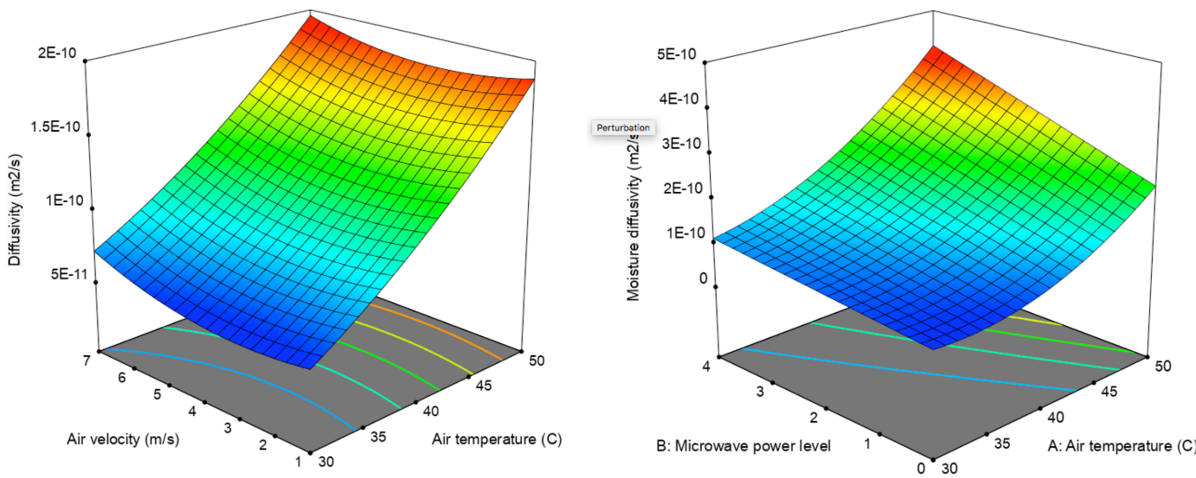


Figure 4.8 Average moisture diffusivity value for various treatments in FBD and MFBD



(a) (b)

Figure 4.9 Moisture diffusivity response chart for (a) FBD and (b) MFBD

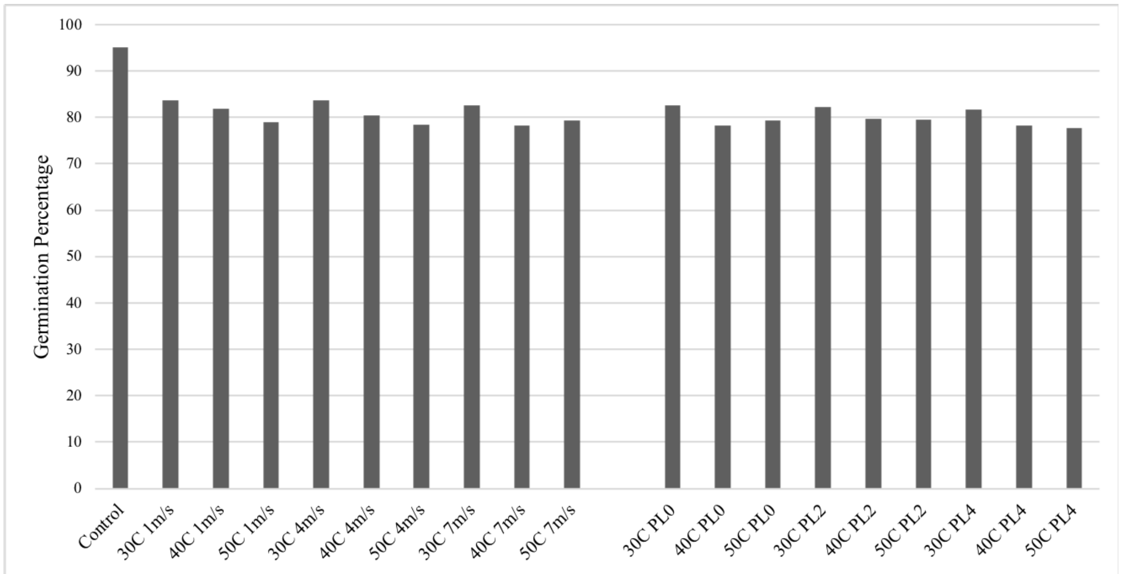
The ANOVA for diffusivity related to FBD and MFBD is shown in Tables 4.3 and 4.4. For fluidized bed drying, the air temperature was significant and air velocity was not having any significant effect on the diffusivity. For microwave assisted fluidized bed drying, air temperature and microwave power level were both significant, with air temperature having more influence on diffusivity than microwave power level. The dependence of diffusivity on the process variables is shown in Figure 4.9 and the modelled equation is shown in Table 4.5.

4.4.4 Seed Quality

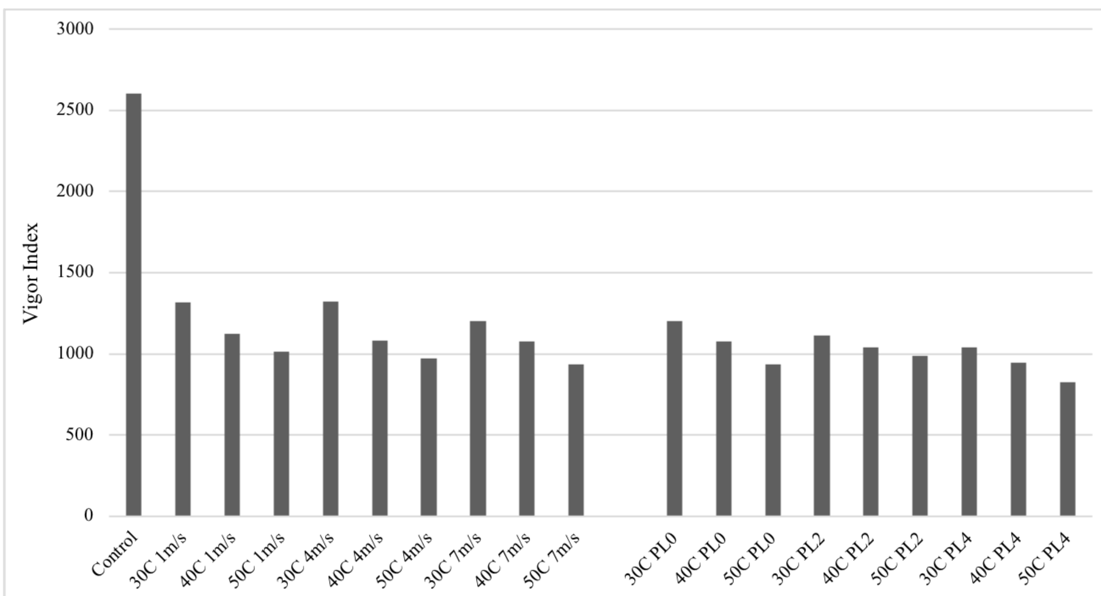
4.4.4.1 Seed Germination and Vigor index

Initial germination of the rewetted seeds was 95% with 2603.7 vigor index. The seeds dried in the fluidized bed dryer had a germination percentage greater than 78% and the seeds dried in microwave assisted fluidized bed dryer had a germination percentage greater than 77% as shown in Figure 4.10 (a). Increasing temperature decreased germination percentage both in fluidized and microwave fluidized bed dryer. Increase in air velocity had a more visible effect at a temperature of 40 and 50 °C. Also, power level 4 had more influence on germination than power level 2. Even though seeds germinated properly but vigor was affected greatly due to drying and the seedling length was reduced in germinated dried seeds than the germinated fresh one as shown in Figure

4.10 (b). Approximately equivalent vigor index was obtained for all drying conditions. Comparable results for germination was obtained in fluidized bed drying for wheat, rice and grass seeds (Fumagalli & Freire, 2007; Jittanit et al., 2013). No literature was found on vigor index of soybean seeds dried in fluidized and microwave fluidized bed dryer. Low vigor seeds lead to an increase in germination time and a reduction in crop yield (Mondo, Nascente, Neto, & Oliveira, 2016).



(a)



(b)

Figure 4.10 (a) Germination percentage and (b) seed vigor at various treatments

Analysis of variance in Tables 4.3 and 4.4 showed that air temperature and air velocity had a significant effect on the germination at 1 and 5% respectively. However, the power level didn’t have a significant effect on the germination, and this shows the possibility of employing microwaves in the drying of soybean seeds at an industrial scale. In the case of the vigor index, air temperature and microwave power level had a significant effect on the vigor index. However, the air velocity effect was not found significant for vigor index. The lack of fit was not significant for both the drying methods and the second order polynomial model is shown in Table 4.5. The response surface chart of germination percentage and seed vigor is shown in Figure 4.11.

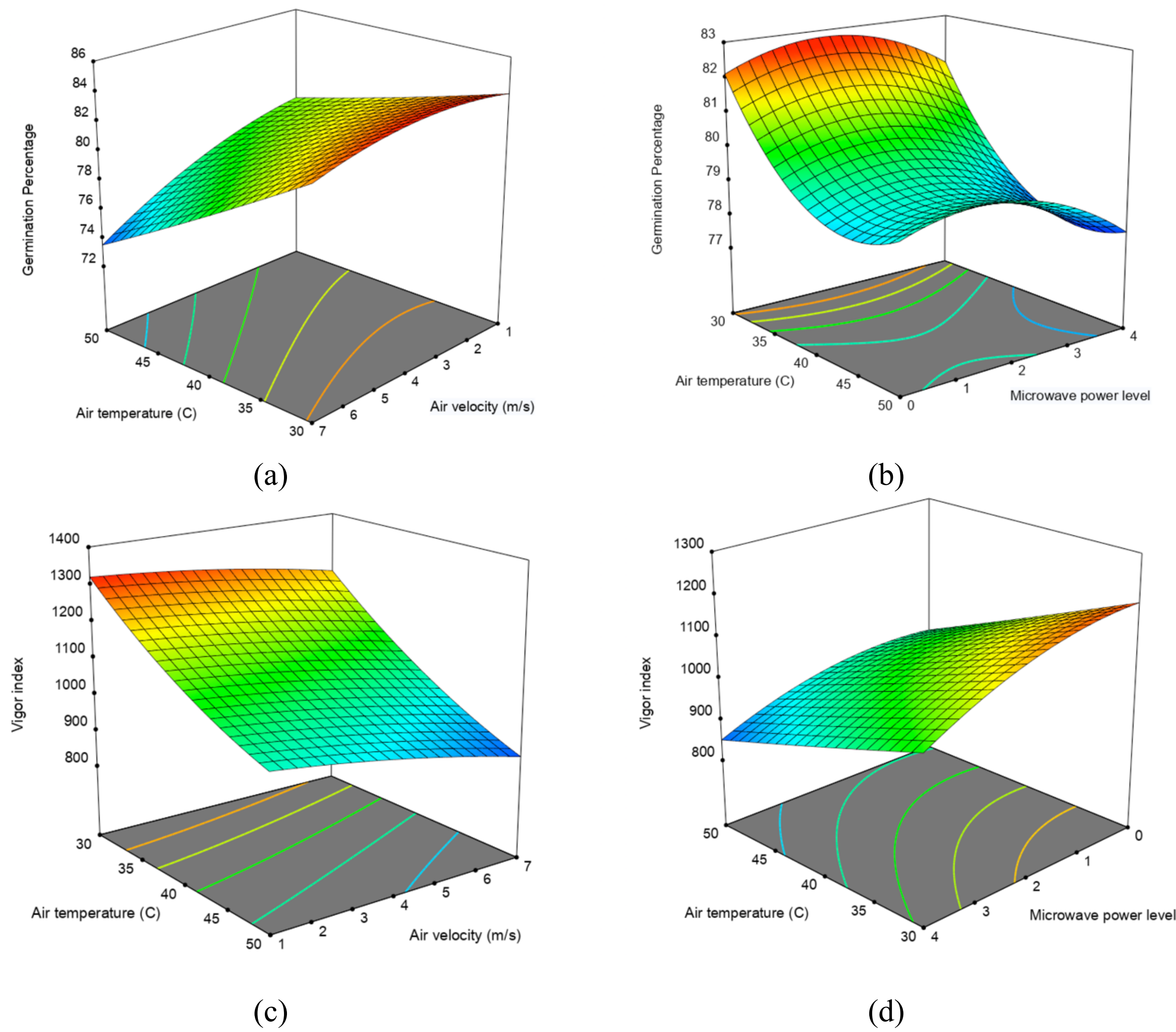


Figure 4.11 Germination response chart for (a) FBD and (b) MFBD and seed vigor response plot for (c) FBD and (d) MFBD

4.4.4.2 Fissures and cracking percentage

Two types of mechanical damages occurred during drying of the soybean. First one is the fissures in the seed coat and the second one was the cracking of the cotyledon. For fresh seeds, the fissure and the cracking percentage was 13 and 0 percent respectively. Fissure and cracking percentages are shown in Figure 4.12 for all the drying treatments. Fissure percentage was low when there was no fluidization but as the fluidization occurred, fissures increased in the seeds. This implies that the seed coat was heavily damaged during drying. In fluidized bed dryer fissure percentage was between 15 to 63% but for microwave fluidized bed dryer it went up to 100%. Fissured seeds are more prone to get spoiled during storage due to electrolytes leaking or microbial attack (Loeffler, Tekrony, & Egli, 1988). Cracking in the cotyledons was low under these drying conditions except for 50 C and power level 4 for which it was around 20%. Two types of cracks were prevalent in the seeds as shown in Figures 4.13 (c) and 4.13 (d). One was along the center of the seeds and the other was along the hilum of the seeds. Fissure occurred all the way horizontally to the center of the seeds and passing through the hilum area as shown in figure 4.13 (b).

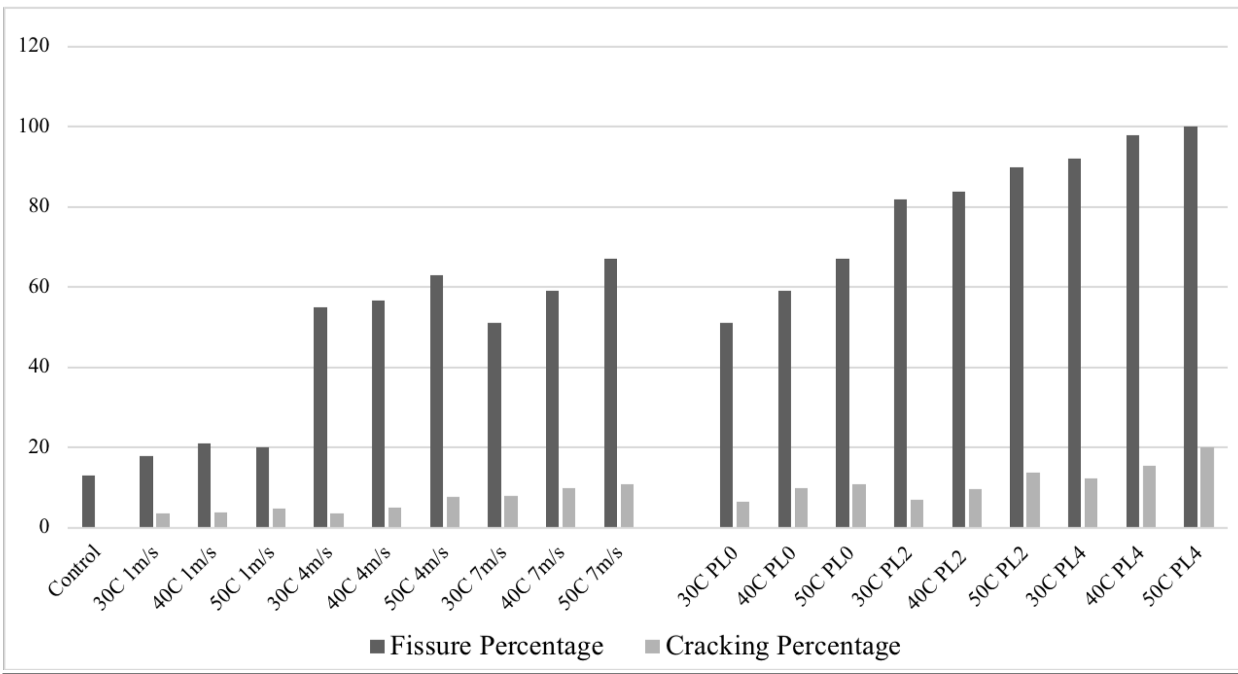
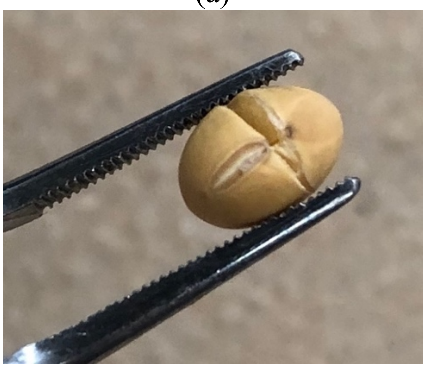


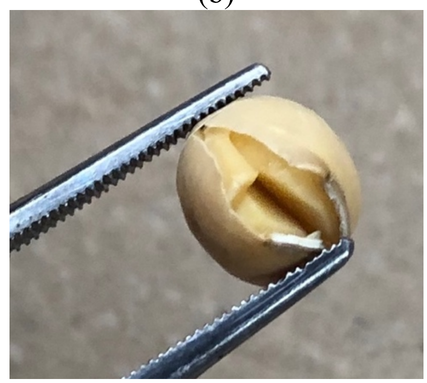
Figure 4.12 Cracking and fissure percentage at various treatments

(a)

(b)



(c)



(d)

Figure 4.13 Images for (a) fresh seeds (b) fissured seeds and Seed cracking along (c) center and (d) hilum

The ANOVA in Table 4.3 and 4.4 showed that the air temperature and air velocity had a significant effect on both fissures as well as the cracking percentage in fluidized bed drying. However, air velocity had a more prominent effect on the fissures and cracking percentage than the air temperature in FBD. This can be attributed to the fact that an increase in velocity resulted in collision with the walls of the chamber and in between the seeds. For microwave fluidization bed drying, air temperature and microwave power level both had a significant effect on cracking and fissure percentage. Equations correlating cracking and fissure percentage for the drying methods are shown in Table 4.5 and the variation of both cracking and fissure percentage is shown in Figure 4.14.

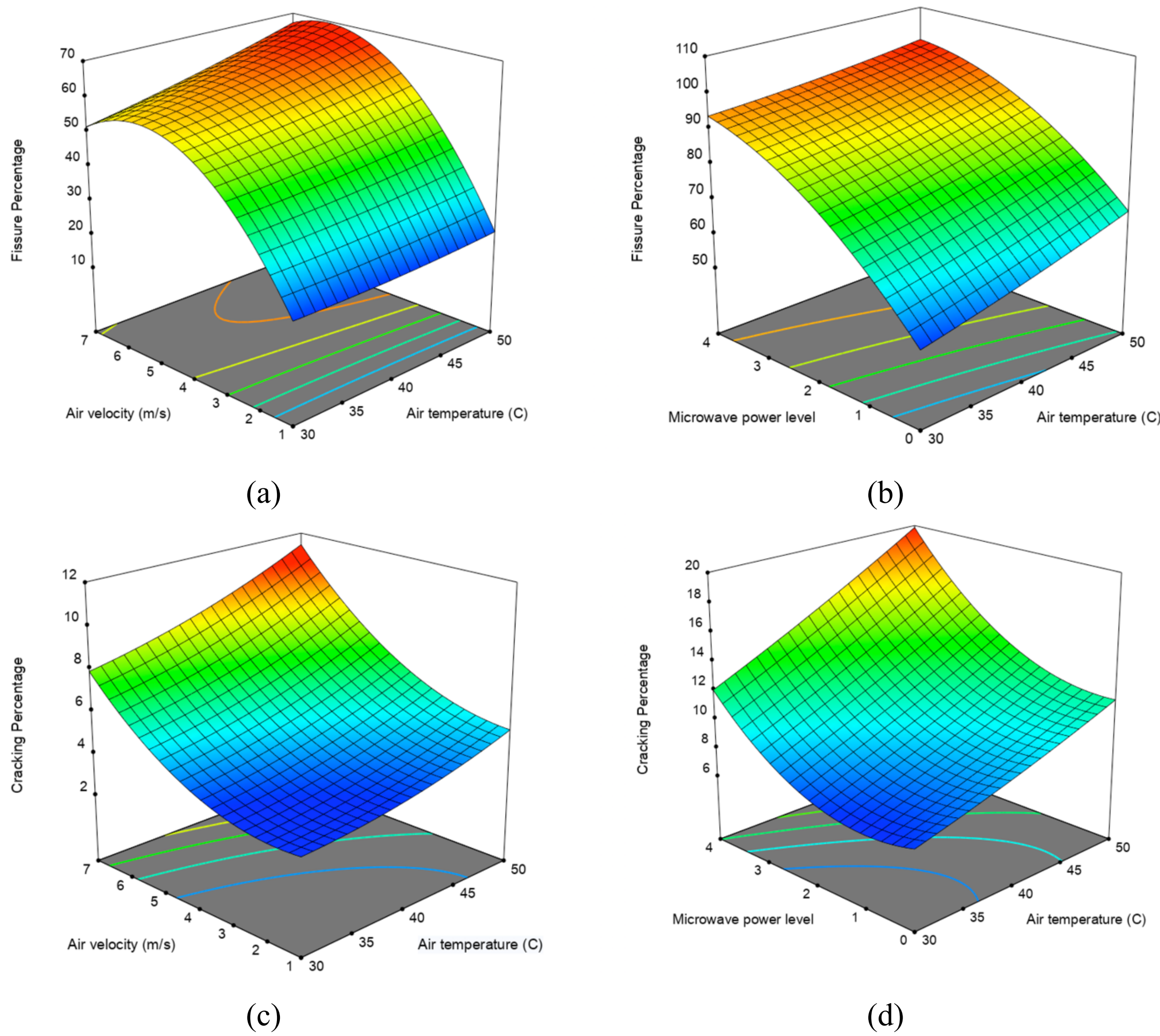


Figure 4.14 Fissure percentage response chart for (a) FBD and (b) MFBD and cracking percentage response plot for (c) FBD and (d) MFBD

4.4.4.3 Seed Coat hardness test

Seeds with hard coat tend to provide protection against pathogens and the mechanical damage; but, seeds with extreme hard coat leads to a dormancy state. The force required to break the extracted seed coat was studied through penetration test and the results are shown in Figure 4.15. It was seen that drying decreased the hardness of the seeds in all drying treatments but there was no trend visible in the decrease of the breaking force. It should be noted that the maximum force required to break the seed coats were lower in microwave assisted fluidized bed drying than fluidized bed drying. It could be due to the volumetric heating in the case of drying assisted by microwaves. No study is reported in the literature for such comparison. Seed coat hardness is an important factor in the longevity of the seeds as it is suggested that seeds with harder seed coat tend to live longer and the weak or brittle coat will alter its resistance to mechanical damage (Sano et al., 2015). This also depicts the reduction of heteropolymer lignin in the secondary cell wall of the coat. Lignin in the seed coat of soybean is already low and it protects the seeds polysaccharides from the microbial attack (Moreira-Vilar et al., 2014).

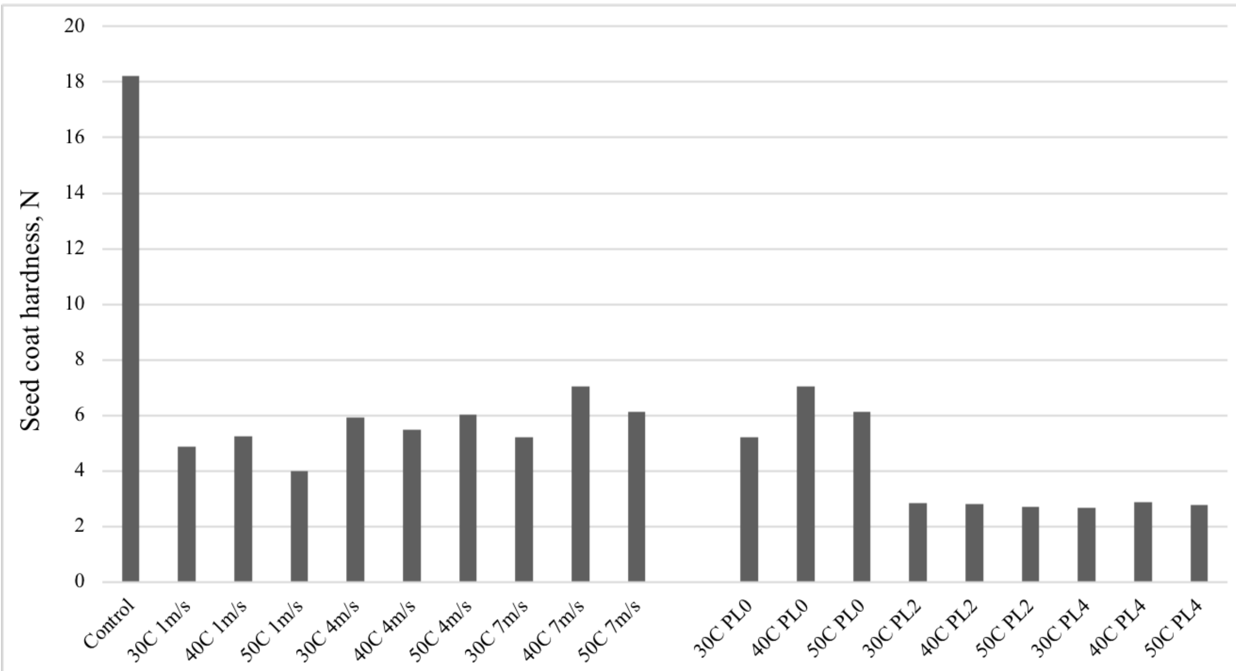
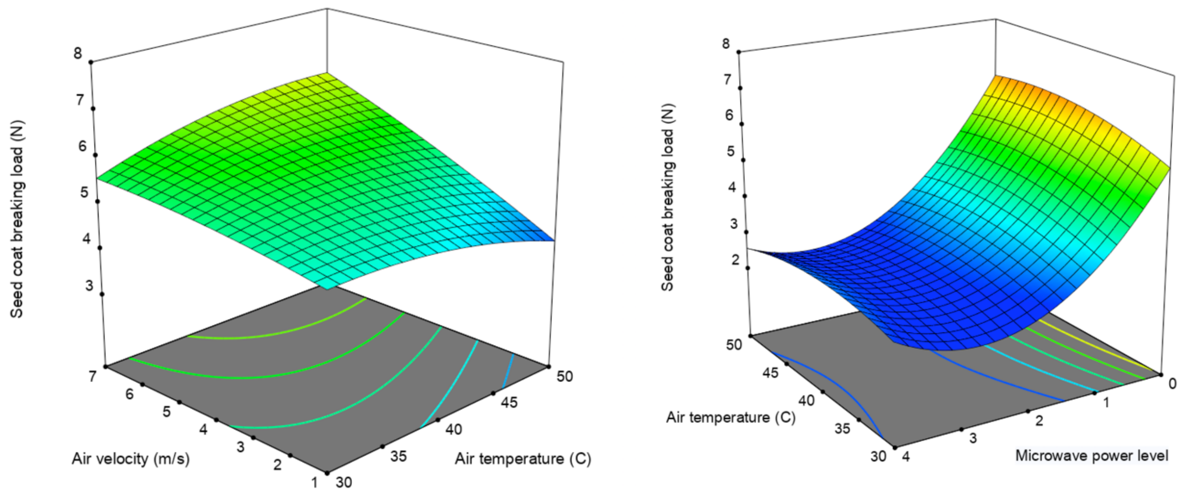


Figure 4.15 Hardness of the seed coat expressed in terms of the breaking load at different treatments

The analysis of variance showed that for fluidized bed drying, input variables were not found significant for hardness. However, for microwave fluidized bed drying of seeds, microwave power level did have a significant effect on the hardness with a significant lack of fit. The response surface for seed coat hardness is shown in Figure 4.16.



(a) (b)

Figure 4.16 Seed coat hardness response surface for (a) FBD and (b) MFBD

4.5 Conclusion

The following conclusions can be drawn from the study carried out here:

1. Fluidized bed drying was able to reduce drying time in comparison to the fixed bed position and hence can be used to reduce heterogeneity in the bed during drying. Drying rate was still low and in that case, microwave assisted fluidized bed drying was able to reduce drying time significantly. In drying kinetics, rate constants and diffusivity have also increased with an increase in drying parameters.
2. Germination potential of the seed was found higher under all the drying methods (>70 %) and this shows the capability of using the aforementioned dryers in the production of seed grade soybean. However, the vigor of the seeds was reduced significantly in dried seeds and the future research including the study of the yield of the crop can give further insight on how the reduced vigor could affect the yield or success of the crop.
3. Mechanical damage in the form of fissures was high in the dried seeds (> 60%) showing that the seed coat was highly damaged during drying. Future research consisting of the study of longevity could help in understanding how these fissures affect the storage ability of the soybean. Also, the soybean seed coat is already thin and low in lignin content (3-

4%) and the type of harvesting method (for example mechanical harvesting or hand harvesting) also result in the reduction of resistance towards mechanical damage. Future studies including a comparison between two harvesting methods can provide sufficient information on its effect on fissures. Also, seed coat hardness was reduced during drying and this shows the possibility of a microbial attack in seeds.

4. For the acceptance of technology, more study on the effect of drying on the seed coat and its properties is required for maintaining seed security and longer shelf life.

Chapter V Summary, conclusion and recommendation for further studies

5.1 Summary and conclusion

Drying is one of the oldest preservation techniques for the food and agricultural products. Over the years, drying technology has evolved and new drying methods have resulted in an energy efficient process with better product quality. Microwave drying which results in the volumetric heating inside the sample provided higher drying rates and better quality of the dried products. In the review paper microwave and various hybrid microwave drying techniques have been discussed. The primary purpose of the review paper was to list recent developments in the field of microwave drying. Microwave drying has proven efficient in the drying of fruits, vegetables and grains. However, in the case of seed grade crops drying, not sufficient studies are reported in the literature. Hence, it was concluded that the study of drying of soybean seeds in different microwave dryers is necessary to draw any conclusions.

In this study, drying kinetics of soybean seeds in air drying, thin layer microwave drying, fixed bed and fluidized bed assisted with the microwave were investigated. Following conclusions can be drawn from the study carried out here:

1) In the first experimental study, thin layer air drying was compared with microwave assisted thin layer air drying of soybean seeds at different temperatures (30, 40 and 50 °C) and microwave power density (0, 0.5 and 1 W/g). It was noted that drying time was significantly reduced in the case of microwave assisted air drying as compared to air drying alone. However, the germination capability and seed vigor was significantly reduced (<35%) in the case of microwave application. Cotyledon cracking was found low (<20%) at all drying parameters but the seed coat was damaged with fissures visible on approximately 85% of the seeds dried with the microwave. Fissures were low in the case of air drying followed by high germination percentage and vigor index. Mathematical modelling showed that both exponential and page model depicts the drying conditions well and the moisture diffusivity value was high in the microwave assisted air drying as compared to air drying. The value of moisture diffusivity was found in good agreement with the standard values for food materials. Moisture diffusion took place as liquid diffusion followed by vapour diffusion in the later part of the drying. Optimization of the

whole drying process showed that approximately no microwave power should be used in the continuous thin layer drying of the soybean for the production of seed grade soybean.

2) In the second part of the study, first fixed bed and fluidized bed drying of the soybean seeds at different temperature (30, 40 and 50 °C) and air velocity (1,4 and 7 m/s) were investigated. The results showed that fluidization assisted in the reduction of drying time but the effect was smaller. Germination percentage was good (>78%) for all treatments but there was a reduction in the vigor index for the seeds. Fissure percentage was high (>60%) in the case of fluidization and the seed coat hardness was reduced. After this, microwave assisted fluidized drying at different temperatures and microwave power levels were investigated and the results showed a significant reduction in the drying time along with the equivalent germination percentage and vigor index. However, fissure seeds reached up to 100% in microwave fluidized bed drying and the seed coat hardness was further reduced as compared to seeds dried in fluidized bed dryer. Modelling predicted that exponential and page model depicts the drying condition well and the moisture diffusivity was higher in the case of microwave assisted fluidized bed drying.
3) Thin layer drying assisted by microwave proved to be unfit for increasing the shelf life of seed grade soybean but the fixed bed and fluidized bed assisted by the microwave was a good fit for the seeds.
4) During drying maintaining germination capability was not a problem in the case of the fluidized bed and the microwave assisted fluidized bed. However, the seed coat damage is the problem encountered during drying.

5.2 Recommendations for further study

1) As the germination speed depicted through vigor index was reduced in the dried seeds. Further research including the study of crop yield related to dried seeds could help in answering the question related to the effect of these reduced vigor.
2) Secondly, the primary purpose of the drying was to increase the storage capability of the seeds. A study including the test of longevity could help in studying the effect of these fissures on the storage ability of the seeds.
3) It is noted that protein and sugar content in the soybean seeds assist in the proper germination capability of the seeds. Also, lignin content in the seed coat help in the protection of the seeds against mechanical injury. A study including the study of these

components after drying could help in depicting how the microwave in different modes affect these contents in the seeds.

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