

DESIGN AND FABRICATION OF DRYING UNIT IN CONTINUOUS THIN FILM MAKING MACHINE

Submitted in partial fulfillment of the requirements for the award of Bachelor of
Engineering Degree in Mechanical Engineering

By

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**DEPARTMENT OF MECHANICAL ENGINEERING
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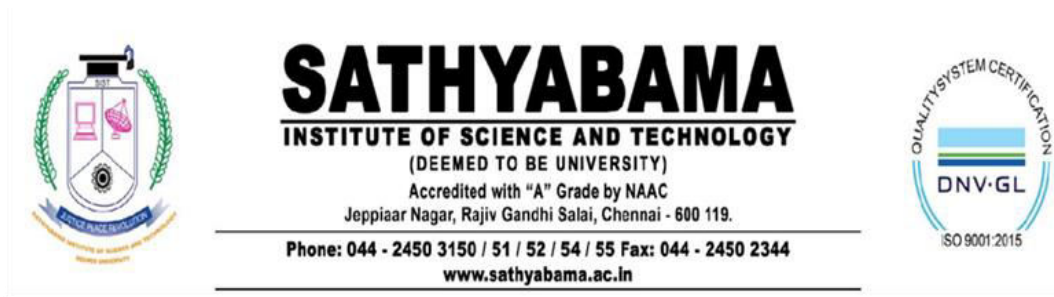
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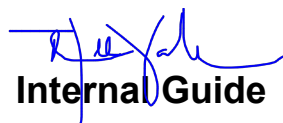
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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of **VENKATESH.T (38150124)** and **LOKESH.N (38150062)** who carried out the project entitled **"DESIGN AND FABRICATION OF DRYING UNIT IN CONTINUOUS THIN FILM MAKING MACHINE"** under our supervision from September 2021 to April 2022



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DECLARATION

We, **T. VENKATESH (38150124)** and **N. LOKESH (38150062)** hereby declare that the Project Report entitled “**DESIGN AND FABRICATION OF DRYING UNIT IN CONTINUOUS THIN FILM MAKING MACHINE**” done by us under the guidance of **Dr. J. JEYA JEEVAHAN M.E., Ph.D.** is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

1) 
2) 

SIGNATURE OF THE CANDIDATES

Date :21-04-2022

Place : Chennai

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ABSTRACT

Edible packaging is a kind of packaging that can be eaten along with the food. polysaccharides, proteins and lipids, are used to make edible packaging. Literature show that the mechanical strength and barrier properties to water vapour and gases (oxygen and carbon dioxide, mainly) of unplasticized edible films made from the native edible polymers are inferior than the petroleum derived plastics. They are also brittle leading to poor flexibility. The addition of plasticizer increased the film flexibility of edible films significantly. Glycerol is the widely used plasticizers to make the edible films. In this research work, a factor at a time investigation was carried out to explore the effects of two factors, namely, (1) starch type, and (2) drying methods, on the film properties of bio nanocomposite edible films. The films produced from wheat, and corn starches could be more opaque than the potato, rice and tapioca starches based films. In order to understand the effects of drying methods, four drying methods, namely, (1) ambient drying, (2) hot air drying, (3) IR drying, and (4) IR plus hot air drying, were considered in the research work. Ambient drying, hot air drying, IR drying and IR plus hot air drying methods could dry the films in 36h, 8 h, 3 h and 2 h, respectively. IR plus hot air drying and IR drying methods could exhibit lower WVTR as compared to ambient drying and hot air drying. IR plus hot air dried films showed the highest TS (26.26 ± 0.41 MPa) and TM (48.54 ± 0.38 MPa) with reduced film

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
WVTR	Water vapour transmission rate
TS	Tensile strength
YM	Young's modulus
EAB or E	Elongation at break
L	Lightness colour parameter
A	Greenness-Redness colour parameter
RH	Relative humidity
°C	Degree Celsius
MPa	Mega Pascal
NA	Not applicable
WVP	Water vapour permeability
LDPE	Low density polyethylene
IR	Infrared radiation
Δ E	Change in colour
RS	Rice starch
PS	Potato starch
CS	Corn starch
TS	Tapioca starch

WS	Wheat starch
GLY or G	Glycerol
MAL or M	Maltitol
SOR or S	Sorbitol
XYL or X	Xylitol
H ₂ O	Water
NS	Nanostarch
NC	Nanocellulose
GPa	Giga Pascal

CHAPTER 1

INTRODUCTION

Packaging is the process of wrapping or enclosing the products for protecting them from damage during handling and transportation. Packaging is one of the inevitable items in many applications like food and beverages, consumer goods, pharmaceutical applications, life style items, cosmetics, clothing, health care, and many others (World Packaging Organization, 2008; Plastics Europe, 2015). The common packaging materials are plastics, paper board, metals, glass, and other materials. With 42% of total use of packaging materials, plastics is the largest used packaging material, due to their easy processing, high performance, light weight, lower cost, and convenience. Within plastic packaging, food packaging is one of the largest plastic consuming sectors with about 54% of share forecasted for the period of 2003-2009. This includes 40% in food and 14% in beverages sectors respectively (World Packaging Organization, 2008). The major functions of food packaging are to (1) store the contained food items, (2) protect them from damage during handling and transportation, or protects them from external influences, and (3) maintain the food quality from the time of packaging to the time of consumption (Ramos et al., 2015; Marsh & Bugusu, 2007; Nilsson & Mortensen, 1999; Zeman & Kubik, 2007).

1.1. PROBLEMS WITH SYNTHETIC/ DEGRADABLE PLASTICS

The use of plastics in packaging, especially, in food and beverages packaging, is not regarded as safe due to various reasons. While the polymer chain is generally considered as inert, the plastic packaging is not inert due to various chemical ingredients. Based on a hazard-ranking model, more than 50% of plastics use hazardous chemical ingredients during processing. The plastic packaging might transfer the volatile plastic molecules, such as monomers, food additives, residual solvents, plasticizers and surfactants, into the stored food. The migration rate is affected by the processing temperatures, storage conditions, storage time, chemical and physical properties of the substances, and interaction with the contained food (Callegarin et al., 1997; Muncke et al., 2014; Arvanitoyannis &

Bosnea, 2004; Lau & Wong, 2000; Hotchkiss, 1997; Begley, 1997; Leufven & Stollman, 1992; Figge, 1980; Rochman et al., 2013).

These plastic molecules can cause various health problems, such as hormone-disruption, reproductive dysfunction, obesity, heart disease, cancer risks, thyroid problems, DNA alternations related to estrogen, reproductive anomalies, breast growth and testicular cancers (Koushal et al., 2014). The exposure of some plastic chemical compounds (having estrogenic activity) can cause early puberty in females, reduced sperm counts in males, obesity, altered functions of reproductive organs, altered sex specific behaviors, diabetes, and increased rates of some breast, ovarian, testicular, and prostate cancers (Yang et al., 2011; North & Halden, 2013; Talsness et al., 2009; Kumar, 2018).

Not only humans, the discarded plastic waste threatens the natural, terrestrial, freshwater, marine and mountain habitats. Substantial amount of plastic waste already contaminated the marine habitats. These plastics may undergo secondary break down reaction (weathering and fragmentaion) and form microplastics, which can greatly affect the marine ecosystem. When these microplastics are ingested by marine organisms, they can produce a range of health effects, such as, blockage in intestinal tracts, inflammation, oxidative stress, hormone disruption, reproductive impact, and metabolic and behavioral changes (Thompson et al., 2009a; 2009b; Wright & Kelly, 2017).

Most of the currently available food packaging use the synthetic plastics for its manufacture. The plastics used in packaging becomes waste after the contained food is consumed. As most of these synthetic plastics are non-biodegradable in nature, the discarded plastic waste does not decompose easily and remain forever as waste in the landfill sites (Ghosh et al., 2013). Despite the fact that the plastic packaging is extremely durable, it is often unnecessary as well as unsustainable. Most of these plastic packaging items used in food packaging applications, such as throwaway cups, plastic bags, spoons, and other utensils, are discarded after the intended purpose. They have very short useful life span ranging from few seconds and minutes to few hours). But, they remain in the landfill sites for decades, centuries, or millennia (Halden, 2010; Hopewell et al., 2009).

The space availability is an important factor to landfill sites. The more rapid the degradation occurs, the larger the space will be available for dumping wastes. Whereas the degradation process produces carbon dioxide under aerobic conditions, the anaerobic biodegradation produces methane as the major product, which is considered as a greenhouse gas having 24.5 times higher impact than does carbon dioxide (Swift, 2015; Vrijheid, 2000). Some countries limit the use of landfill sites for the waste disposal. The space availability for landfills is a major issue in many countries, especially, in highly populous cities (Barrow, 2005; Lowe, 2009; Ham, 1993; Rahman, 2013). Recycling can help reduce the landfill problem. However, plastics discarded after the consumption of the contained food is recycled in a very limited quantity. Plastics are either dumped in landfills or burnt for energy recovery. Dumping plastics in landfills remains forever. If incinerated for energy recovery, it may produce harmful gases, which can cause air pollution.

Another problem with plastics is its dependency on petroleum reserves. The increasing oil prices might also impact on the price of plastics in the near future. The dependency of petroleum reserves and the increasing price of plastics can be overcome by replacing the plastics with the renewable polymers for the sustainable and eco-friendly plastics (Mülhaupt, 2012; Halden, 2010; Andrady & Neal, 2009; Demirbas, 2007).

People often believe that all degradable and biodegradable polymers can overcome the problems associated with the non-degradable plastic packaging. But, in reality, most of these, so called, degradable polymers often disintegrate them into small pieces, after which the degradability is not more than the synthetic plastics. Another concern is that they do not degrade quickly in natural habitats, which can cause the health problems. Though degradable polymers are beneficial to reduce the waste disposal problems, the degradable polymers are not yet good for environment and health (Thompson et al., 2009). The degradation rates of degradable polymers vary depending on the local environmental factors and physical factors, such as exposure to ambient air and ultraviolet light, and temperature, while biodegradable polymers require the suitable micro-organisms

and their growing conditions (Hopewell et al., 2009). Since landfills reduce the presence of oxygen and moisture which are essential for biodegradation, biodegradability of the degradable polymers is significantly affected. Moreover, land space is still required for storing wastes until they are fully decomposed. Therefore, biodegradable materials show little impact on reducing landfills (Marsh & Bugusu, 2007; Kale et al., 2007).

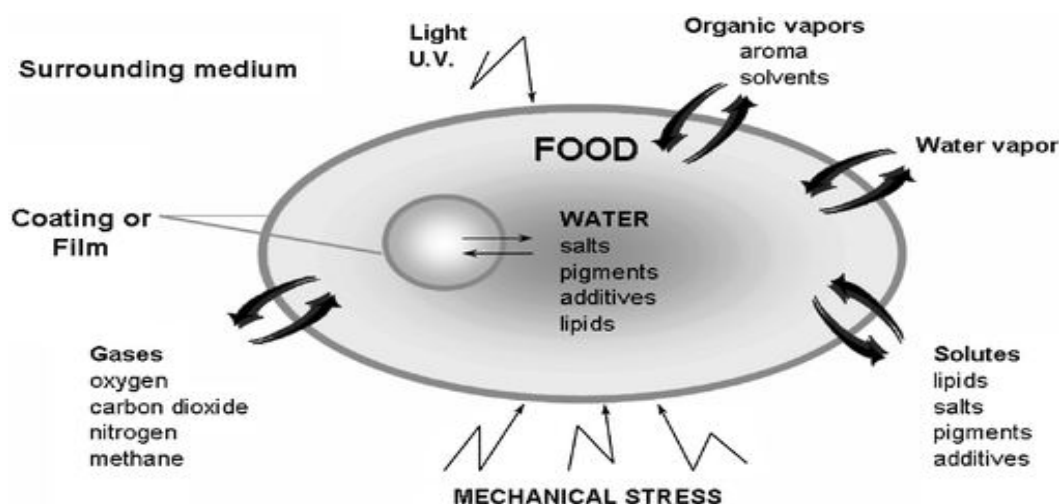


Fig: 1.1: Potential migrants of the edible films (Debeaufort & Voilley, 2009)

Fig 1.1. shows the potential migrants of the edible films between the contained food and the surrounding. The qualities of an ideal edible packaging material are listed as follows (Pavlath & Orts, 2009; Debeaufort & Voilley, 1994; Debeaufort et al., 1998; Siracusa, 2013; Otoni et al., 2017):

- It should not contain any toxic, allergic and non-digestible ingredients.
- It should provide sufficient structural stability to prevent mechanical damage during transportation and handling.
- It should display good adhesion with food surface for uniform coverage.
- It should control the migration of water vapors coming in and going out of it to maintain a desired moisture level.

- It should be semi-permeable to gases responsible for aerobic and anaerobic respiration for retarding senescence.
- It should not alter the aroma, flavor, nutritional, sensory and organoleptic characteristics, which are important for consumer acceptance.
- It should protect against contamination, pest infestation, microbe proliferation, and other types of decay.
- It should serve as carrier for desirable additives such as flavor, fragrance, coloring, nutrients, vitamins, antioxidants and antimicrobial agents.
- It should easily be processed and manufactured.
- It should be economically feasible.

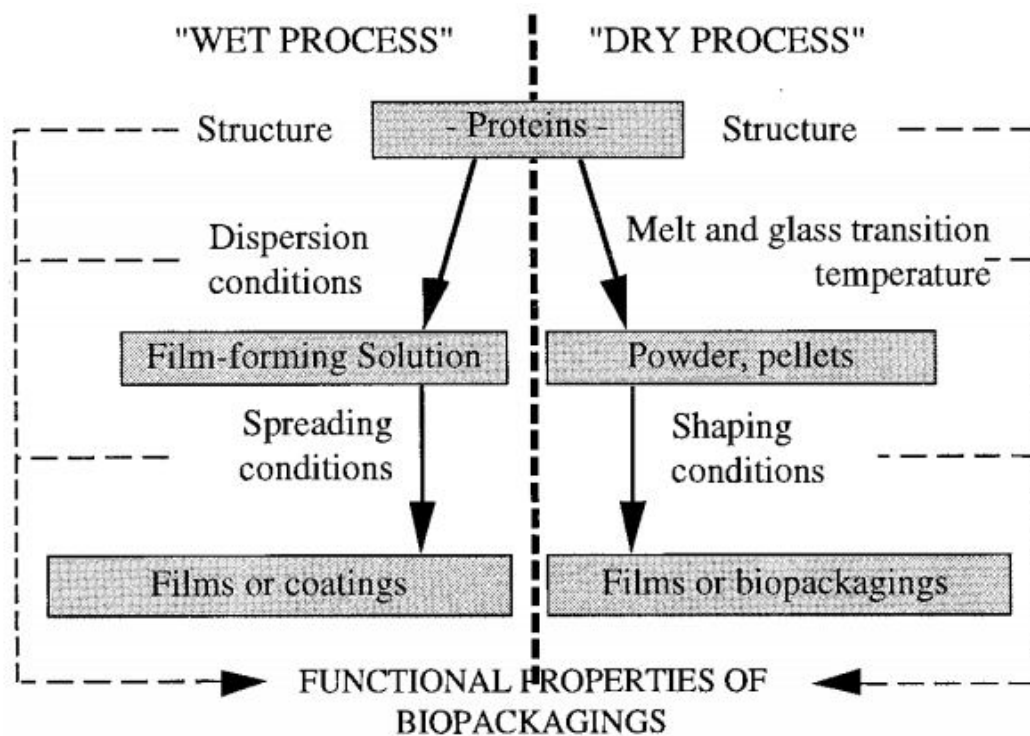


Fig: 1.2: Film forming methods

Two methods are commonly used for making edible films and coatings: (a) dry process and (b) wet process. In dry process, the films and coatings are prepared under low-moisture environment by thermal or thermo-mechanical treatments. In

this method, thermoplastic raw materials are heated to a temperature above glass transition temperature to form soft and rubbery materials and are molded to form the desired shape of the edible film and coatings. Cooling the mold to room temperature produces the desired edible film or coating in a more rigid form. In wet process, the raw material is first dispersed or solubilized to form liquid phase. The dispersed material is then poured into a leveled surface (casting or spreading) or applied directly on the food products (Guilbert et al., 1997; Jimenez et al., 2012).

1.2. POPULAR EDIBLE PACKAGING MATERIALS

There are three major classes of edible polymers used to make edible packaging. They are polysaccharides, proteins and lipids.

Polysaccharides are homo-polymers consisting of a repeating units of monomer, such as glucose, while proteins are hetero-polymers consisting of more than at least 20 amino acids. While edible films produced from polysaccharides exhibit poor mechanical strength, the proteins-based edible films offer good better mechanical strength due to their complex nature of amino structure. As both polysaccharides and proteins are hydrophilic in nature, the edible films made from them exhibit poor water resistance. Lipids, on the other hand, are hydrophobic in nature and they exhibit good resistance to water transmission. But, lipids are not capable of forming the self-supporting film structures. Hence, lipids can be used as a edible coating or as an additive along with polysaccharides and/ or proteins in order to form the composite films (Janjarasskul & Krocha, 2010; Bourtoom, 2008).

1.3.1. Functional Properties

The functional properties of the edible films are the essential properties that describe the performance and suitability to a particular application. In this research work, three major functional properties, namely, (1) mechanical strength, (2) water vapor transmission rate (WVTR) and (3) film color, were considered. High mechanical strength is required to protect the contained food from the external loads. WVTR is the degree of resistance offered by the edible films to prevent

migration of water vapor between the contained food and the environment. Film color is another important property that influences the consumer acceptability of edible films. On the other hand, EAB of edible films is very low as compared to petroleum derived plastics, which indicates that the edible films are highly brittle, leading to poor flexibility.

1.3.2. Film Manufacturing and Drying Methods

Casting is one of the most used film making methods for the laboratory-scale production of edible films. In this method, the film forming solution is prepared first and heated to a gelatinization temperature in order to form a gel-like material. This gel-like material is then spread onto a surface and dried to form the films. These cast films contain high amount of water that is evaporated using the energy-consuming drying methods (Thunwall et al., 2008). Most of these edible films are evaporated by hot air, which is considered to be a very slow process. It, sometimes, takes about 2-3 days for drying the edible films. There are other drying methods that could minimize the drying time. For example, vacuum drying, conduction, infrared drying and low-pressure superheated steam drying were used to dry the edible films in less than two hours (Mayachiew & Devahastin, 2008; De Moraes and Laurindo, 2017; Ortiz et al., 2017). In the work of Kaya & Kaya, 2000, the microwave drying was used to dry the edible films in 5 min without significant difference in WVP. While most of the research works focused on the fabrication of edible films on lab-scale or batch size, the continuous formation of edible films is another problem with the edible films. Munhoz et al. (2018) proposed a continuous fabrication method to produce the continuous edible films in which the film forming solution was spread in a moving conveyor and dried using both an IR pre-dryer and hot air drying. The results reported the total drying time as 7 min and productivity as 0.03 m² film/min. There is an immediate attention required in order to low cost, energy-efficient and high production for the industrial scale production of edible films.

CHAPTER 2

LITERATURE SURVEY

Mayachiew and Devahastin in 2008 find the effects of drying method by using low pressure saturated steam dried films were more strong and resistant to water vapors, compared to the vacuum dried films, hot air dried films and cast films.

Cardenas et al, in 2008 find that cast films were good barriers to water vapors as compared to microwave heat dried films. However, this difference is not significant. Microwave heating is faster about six times than the air heating. Moreover, microwave heating exhibited the smooth surface and improved UV-vis light barrier properties.

Kaya and Kaya, 2000 find that microwave dried films show better mechanical strength, same water barrier properties and appearance as compared to the oven dried films.

Ortiz et al., 2017 assume that infrared radiated films can produce films with clear, but slightly lower mechanical strength and water resistance as compared to hot air dried films.

Alcantara et al 1998 define that drying rate depends on several factors, such as the exposed area, drying temperature, drying air velocity, relative humidity and drying time.

Silva et al 2012 state that ambient and hot air drying methods , the moisture removal rate is greatly affected by the surface evaporation through convection ,which requires sufficient migration of the water molecules from the core so as to make the surface remain in wet condition.

Kchaou et al., 2019 ; Mayachiew and Devahastin .,2008; Silva et al., 2012 described that at high temperatures, the heat supplied and the moisture diffusivity would be higher ,and hence the drying time decreases with the drying temperature.

Srinivasa et al., 2004 and Fernandez-Pan et al., 2010 reported that heat dried films were more resistant to water vapours as compared to the air-dried films.

Mayachiew and Devahastin ,2008 proved that slower drying provides more time for the polymer chains to rearrange themselves so that they form more crystals.

Homez -Jara et al .,2018 define that film forming solution was dried for a long drying time ,water would be well incorporated into the polymer structure of the binonanocomposite edible films leading to high elongation at break .

Srinivasa et al., 2004 declare that oven drying , the drying occurred in the surface layers of the film forming solutions ,and this kind of preferential drying of surface layers could be attributed to Maillard reactions products. The hot air in the oven drying could make the films become more yellowish or brownish .

CHAPTER 3

AIM AND SCOPE

3.1. AIM:

1. To Design the drying unit for continuous edible film making machine.
2. To fabricate the drying unit for continuous edible film making machine.
3. To evaluate the effects of design parameters on the drying unit properties for continuous edible film making machine.

3.2. SCOPE:

Edible films and coatings based on milk proteins have been developed to be used as a protective layer on foods or between food components. The most important function of an edible film to control mass transfers, mechanical protection, and sensory appeal. It eliminates the recycling process.

CHAPTER 4

MATERIALS AND METHODOLOGY

This chapter discusses about the materials used and the fabrication methods followed to make the edible films, procedures followed to extract the nanofillers and the procedures followed to measure the film properties of the edible films.

4.1. MATERIALS

Different sources of food grade edible polymers were used to form the native edible films. Potato starch, tapioca starch, wheat starch, rice starch and corn starch with at least 98% purity were purchased from Urban Platter Food Corporation, Mumbai, India. Whey protein isolate and soy protein isolate, and coconut oil with at least 98 % purity were purchased from local market in and around Chennai, India. Different food grade plasticizers were used to improve the film flexibility. Polyols (glycerol, maltitol, sorbitol & xylitol), glycol (polyethylene glycol) and sugars (Sucrose) were purchased from Sri Amman Scientific And Surgicals, Chennai, India.

4.2. DRYING METHODS

4.2.1. Natural Evaporation

In this drying method, the edible films are dried in sunlight or under ambient conditions. When dried in sunlight, the films were dried in 8-12 hours depending upon the amount of sunlight. When dried at room temperature, the drying time was about 3-5 days depending upon the amount of sunlight.

4.2.2. Hot Air Blowing

Fig. 4.1. shows the drying set up for the hot air blowing. In this drying method, a heater with fan setup was used to dry the edible films. Hot air (at about 50 °C) was blown over the film surface continuously to reduce the drying time. The drying time varied from about 4-8 hours.



Fig: 4.1: Drying of edible films using hot air blowing

Polymer chains could get sufficient time to rearrange themselves within the polymer network. But at the higher drying rate, there could be less chance of the complete rearrangement of such polymer networks. Hence, the tortuosity of the film structure would increase, which, in turn, could become the obstacles to resist.

4.2.3. Infrared Radiation (IR)

Fig. 4.2. shows the drying set up that uses infrared radiation for drying the bionanocomposite films. In this drying method, an infrared drying unit was fabricated with infrared lamps (Phillips, 500 W Helium bulbs) were placed over a flat surface. The distance between the flat surface and the lamps was about 15 cm. The drying time in this case was about 2-3 hours.

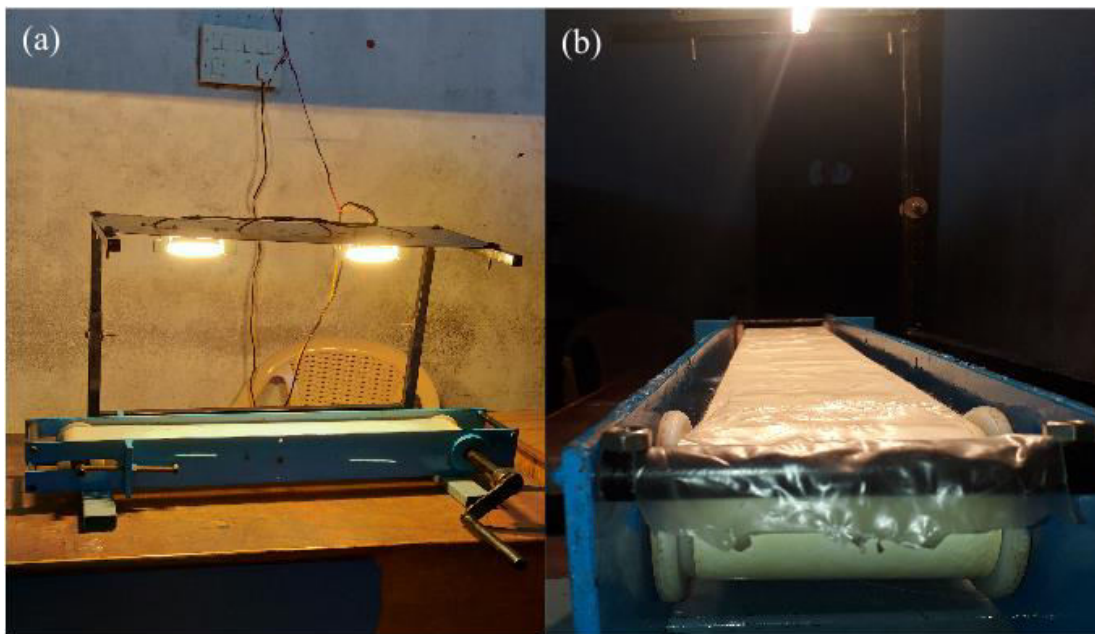


Fig: 4.2: Drying of edible films using infrared radiation

4.2.4. Infrared Radiation (IR) Plus Hot Air Drying

Fig 4.3. shows the drying unit that consists of both infrared radiation and hot air blowing. In this drying method, the combination of infrared drying unit and hot air drying unit were used together. The bio nanocomposite films were first dried using the IR rays. After that, the films were passed to the hot air blowing setup where the heated air is blown over the film surface. The drying time in this case was about 2 hours.



Fig: 4.3: Drying of edible films using infrared radiation plus hot air

CHAPTER 5

RESULT AND DISCUSSION

Drying time is one of the important factors to be considered for the industrial scaling up of the bio nanocomposite edible films. Most of the laboratory scale production of edible films was done using the free casting method with convective evaporation in ambient conditions. It usually takes 1-3 days for drying the edible films. Long drying time makes the edible films not viable for the scaling up production in industrial scale. Therefore, the effective drying methods should be developed so that the drying time is minimum without the penalty on the film properties. This chapter discusses the effects of drying methods on the film properties of edible films produced from potato starch plasticized with 14 w/v xylitol and 10% nanocellulose. Four drying methods, namely, (1) ambient drying, (2) hot air drying, (3) IR drying, and (4) IR plus hot air drying, were considered in the research work. The bio nanocomposite films dried in ambient conditions were considered as the control films.

5.1. INFLUENCE OF DRYING METHODS ON DRYING TIME

Fig. 5.1. shows the effects of drying methods on the drying time of the bionanocomposite edible films produced from the potato starch, xylitol and nanocellulose.

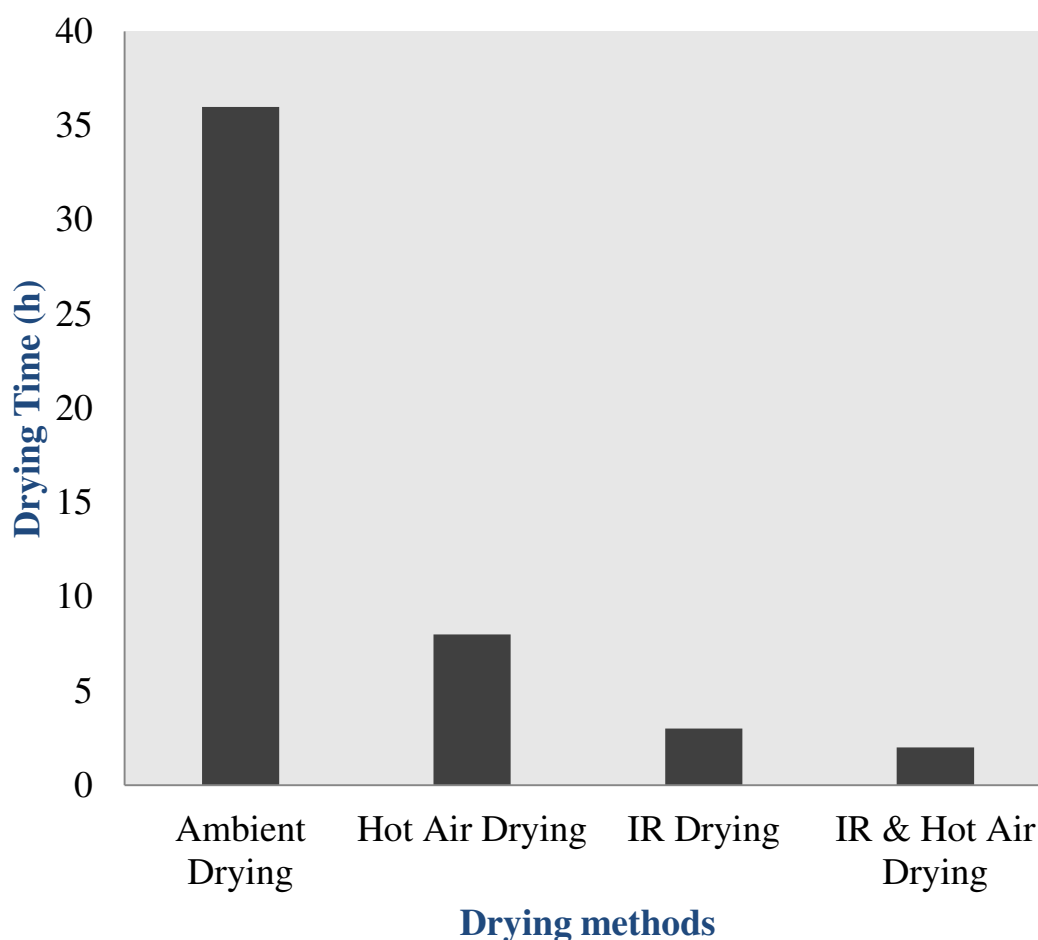


Fig: 5.1: Drying methods and the drying time of edible films

The results showed that the drying time of ambient drying method was about 36 h, whereas hot air drying, IR drying and IR plus hot air drying methods could dry the films in 8 h, 3 h and 2 h, respectively. The drying process involves heat as the input and the removal of moisture as the output. The drying rate depends on several factors, such as, the exposed area, drying temperature, drying air velocity, relative humidity and drying time (Alcantara et al., 1998). In case of ambient and hot air drying methods, the moisture removal rate is greatly affected by the surface evaporation through convection, which requires sufficient migration of the water molecules from the core so as to make the surface remain in wet condition (Silva et al., 2012). At high temperatures, the heat supplied and the moisture diffusivity would be higher, and hence the drying time decreases with the drying temperature (Kchaou et al., 2019; Mayachiew & Devahastin., 2008; Silva et al., 2012). Therefore, the ambient drying and IR plus hot air drying were the slower and the

faster among the four drying methods to produce the bionanocomposite edible films.

5.2. INFLUENCE OF DRYING METHODS ON WVTR

Fig. 5.2. shows the effects of drying methods on WVTR of the bionanocomposite edible films.

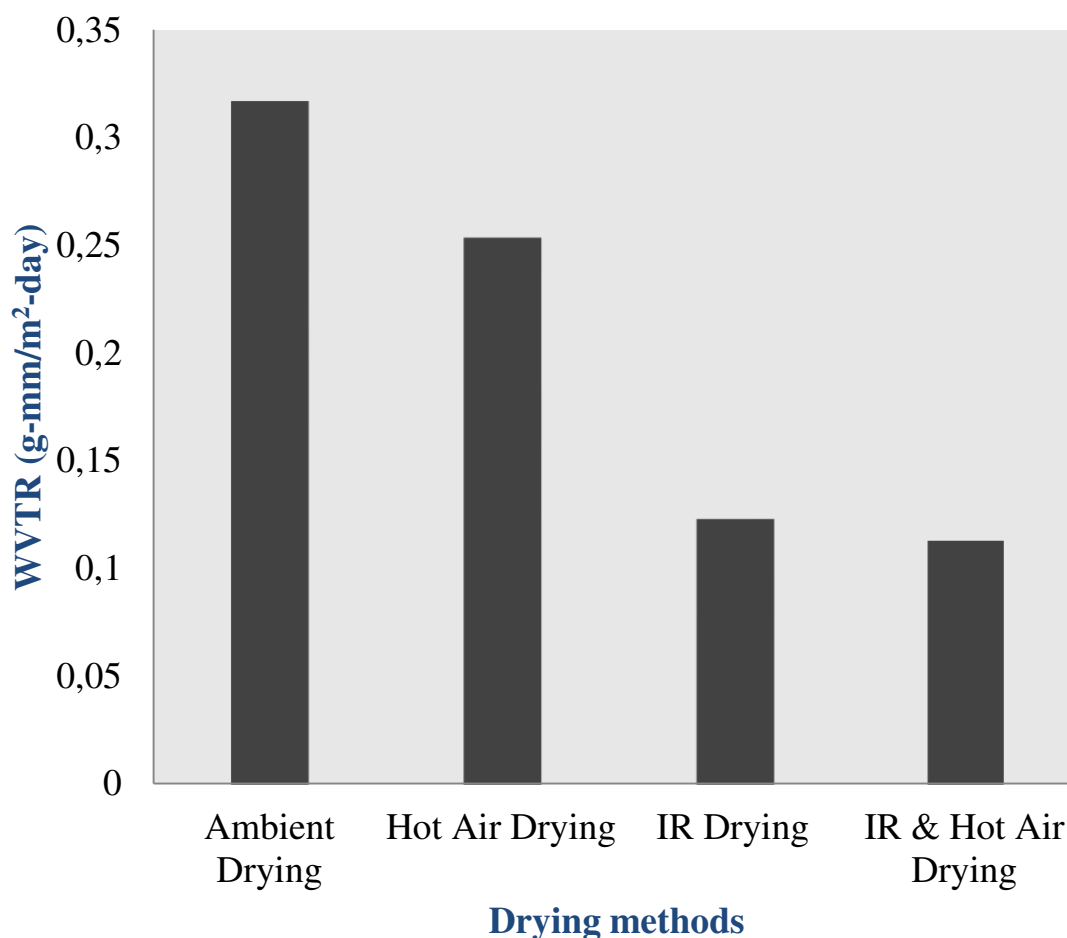


Fig: 5.2: Drying methods on WVTR of the edible films

The results showed that WVTR of the control films was found to be 0.317 ± 0.034 g.mm/m².day. Hot air drying, IR drying and IR plus hot air drying could produce the bionanocomposite films with WVTR of 0.254 ± 0.039 g.mm/m².day, 0.124 ± 0.07 g.mm/m².day, and 0.114 ± 0.014 g.mm/m².day, respectively. From these results, it was found that the heat-dried films were more resistant to water vapours as compared to the air-dried films. Similar result was reported by Srinivasa et al. (2004) and Fernández-Pan et al. (2010), and, hence, the results were in good

agreement with the literature results. The drying time affected the WVTR of the bionanocomposite films significantly. At slower drying rate, the. While both ambient air drying and hot air drying methods removes the moisture on the surface of the film forming solution, IR drying removes the moisture from inside the core. It was also learnt that after the water evaporates, the heat could react help make the thermal linkages and the malliard the migration of water molecules. As a result, the WVTR would be reduced in the case of higher drying rate reaction products, which would further increase the tortuosity. Hence, IR drying would not only reduce the drying time but also reduce the WVTR considerably as compared to air drying methods. Further, While hot air drying dries the film through surface convection, IR drying dries the film from inside. Therefore, the IR plus hot air method provides the combinational effects on the WVTR of the films. As surface and core drying occurred simultaneously, the drying time as well as WVTR of the films were found to be lower compared to other drying methods.

5.3. INFLUENCE OF DRYING METHODS ON TENSILE PROPERTIES

Fig. 5.3. and Fig. 5.4 show the effects of drying methods on TS and YM of the bionanocomposites. From the results, it was found that the ambient drying could produce films with lesser TS and YM, as compared to the remaining drying methods. Similar results were reported in literature by Kchaou et al. (2019) Mayachiew & Devahastin (2008), Mayachiew et al. (2010a, 2010b), and Srinivasa et al. (2004), and, therefore, the results are in good agreement.

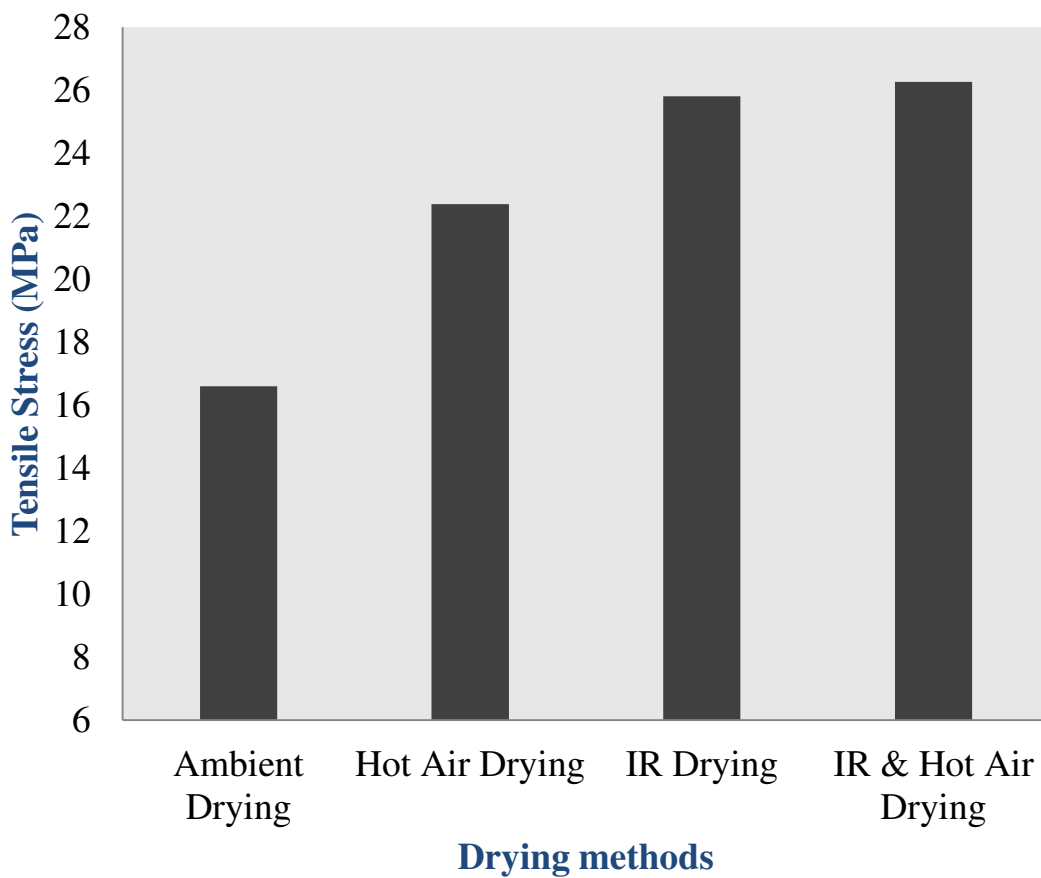


Fig: 5.3: Drying methods on TS of the edible films

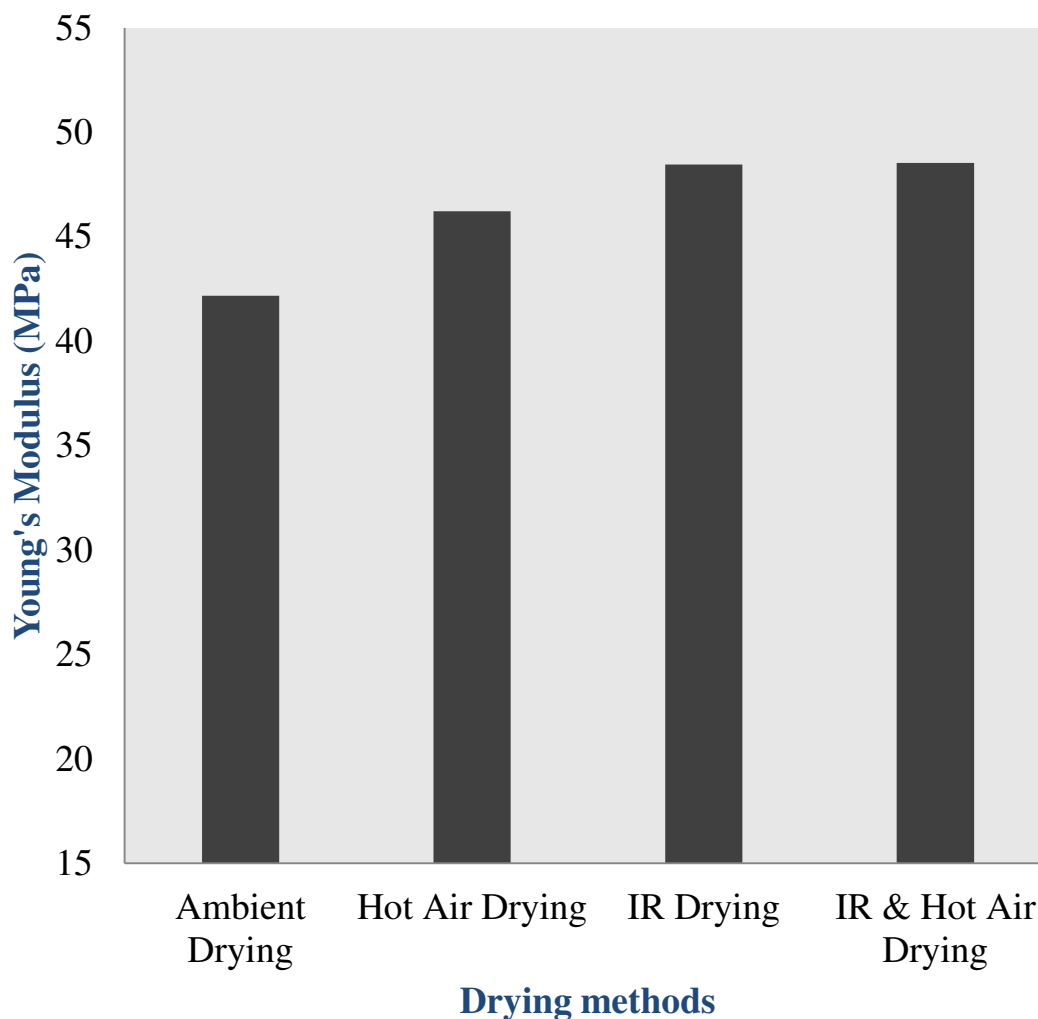


Fig: 5.4: Drying methods on YM of the edible films

TS and YM of the control films produced at ambient drying were 16.6 ± 0.53 MPa and 42.18 ± 0.9 MPa, respectively. Hot air drying method could produce the films having TS of 22.38 ± 0.95 MPa and YM of 46.22 ± 0.44 MPa, respectively. IR drying produced the films with TS and YM of 25.8 ± 0.8 MPa and 48.46 ± 0.83 MPa, respectively. TS and YM of the IR plus hot air dried films were 26.26 ± 0.41 MPa and 48.54 ± 0.38 MPa, respectively. Literature says that the mechanical strength of the composite films depends on the degree of crystallinity. As the degree of crystallinity increases, the mechanical strength increases. The degree of crystallinity, on the other hand, depends on the drying time and drying temperature. Slower drying provides more time for), Wiset et al. (2014) and Kaya & Kaya (2000). This might be explained by the effect of the higher drying

temperature. Higher temperature could induce more thermal cross-linking within the films. This promotes the the polymer chains to rearrange themselves so that they form more crystals (Mayachiew & Devahastin, 2008). This indicated that the TS and YM could decrease for the faster drying time. Similar results were also reported by Thakhiew et al. (2010) and Srinivasa et al. (2004). However, our results showed that the increase of drying temperature and faster drying time had resulted an increase of TS and YM of the bionanocomposite films. Similar increase of TS and YM of the films due to the increase of drying temperature was reported by Mayachiew & Devahastin (2008), Alcantara et al. (1998), Kayserilioğlu et al. (2003) interactions. Hence, with the faster drying cycles and higher drying temperatures, the mechanical strength could have increased (Mayachiew & Devahastin, 2008; Homez-Jara et al., 2018). When the drying time was less, there was no adequate time given for the rearrangement of polymer chains. Therefore, they form the complex network of starch polymer, nanocellulose, and glycerol. This complex network could become the obstacles requiring more stress to deform. Therefore, TS and YM of the bionanocomposite films could be higher if the drying time was less.

Fig. 5.5. shows the effects of drying methods on the elongation at break of the bionanocomposite edible films. It was found that the drying methods significantly affected the elongation at break of the films. While the highest 'E' was found in ambient drying method, the films produced from other methods reduced the elongation at break, indicating the reduction of ductility.

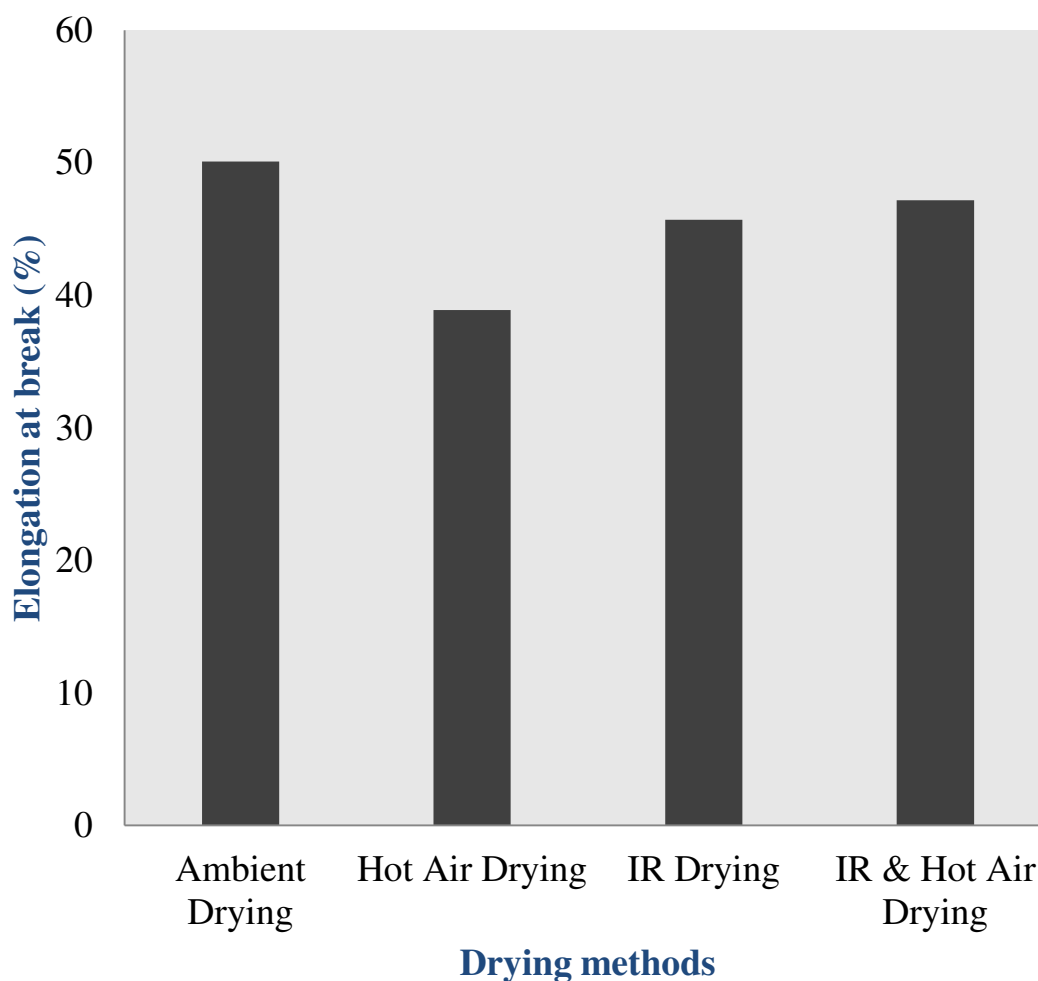


Fig. 5.5: Drying methods on 'E' of the edible films

While the ambient-dried bionanocomposite films showed the 'E' of 50.1 ± 4.96 %, 'E' values of hot air drying, IR drying and IR plus hot air drying were found to be 38.88 ± 0.62 %, 45.7 ± 0.9 %, and 47.18 ± 0.71 %, respectively. The drying temperature provided the inversely proportional effect on the elongation at break. That is, 'E' decreased with the increase in the drying temperature. The films exposed to longer drying time and low drying temperature resulted the reorganization of the polymer network. The long-term interactions, due to hydrogen bonding and Van der Waals bonding, could have been formed. This, in turn, could have produced the ordered network. However, when this transport phenomena occurs at higher drying temperatures, the formation of polymer network would be limited due to rapid water evaporation. The resulting film would be disordered. Also, when the film forming solution was dried for a long drying

time, water would be well-incorporated into the polymer structure of the bio nano composite edible films, leading to high elongation at break (Homez-Jara et al., 2018). As a result, the ambient dried films exhibited high ductility and hence high film flexibility. As the bio nanocomposite films, dried from hot air drying, IR drying and IR plus hot air drying, were dried at higher drying rates, they could not form the ordered structure. Therefore, the elongation at break of the bio nanocomposite films dried with higher drying temperature were found to be lower as compared to the films dried from ambient drying.

5.4. INFLUENCE OF DRYING METHODS ON FILM COLOUR

Fig. 5.6., Fig. 5.7. and Fig. 5.8. showed the effects of drying methods on the film colour of the bio nanocomposite films. The results showed that the bio nanocomposite films dried in ambient drying showed higher 'L' values and lower 'B' as compared to other drying methods. As the drying temperature increased, 'L' of the bio nanocomposite films was decreased and 'B' was increased. There is no significant difference in 'A' of the bio nanocomposite films among the drying methods.

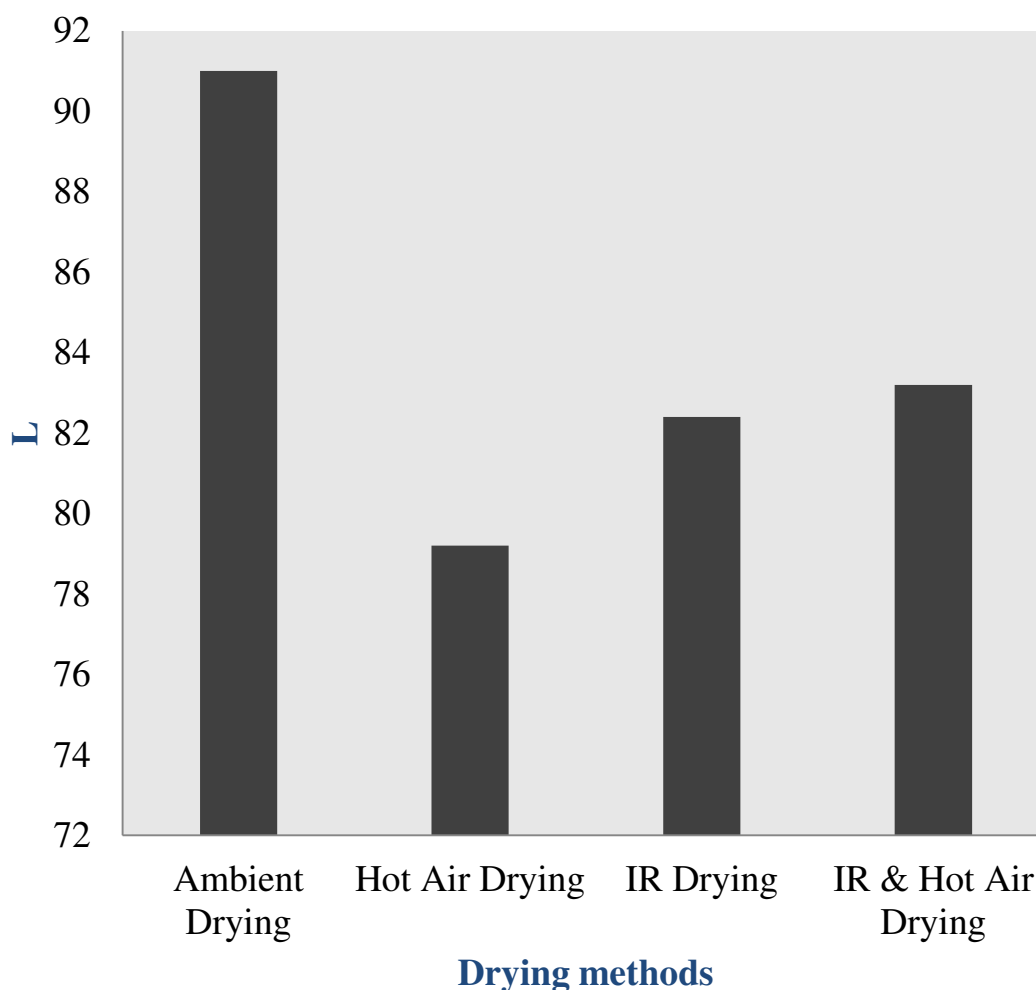


Fig: 5.6: Drying methods on 'L' of the edible films

The lightness 'L' of the ambient air dried films was found to be higher than the rest, indicating that the ambient drying could produce relatively more transparent films. The reduction of 'L' due to the increase of the drying temperature was also reported by Srinivasa et al. (2004), Thakhiew et al. (2010), Mayachiew & Devahastin (2008). Higher drying temperatures could lead to slightly darker films due to browning effects. Higher drying temperatures could rapidly deplete water molecules and react with the film forming solution and can form the maillard reaction products. These maillard reaction products reduce the transparency of the bionanocomposite films (Mayachiew & Devahastin, 2008). Furthermore, due to rapid drying, there was no adequate time for the rearrangement of polymer chains, causing less crystallization. Due to reduced degree of crystallization, the transparency of the bionanocomposite films could be lower for the films dried in

higher drying temperatures, which, in turn, could have reduced the 'L' colour parameter of the bionanocomposite films. Therefore, the films dried using ambient drying were found to be more clear than other films.

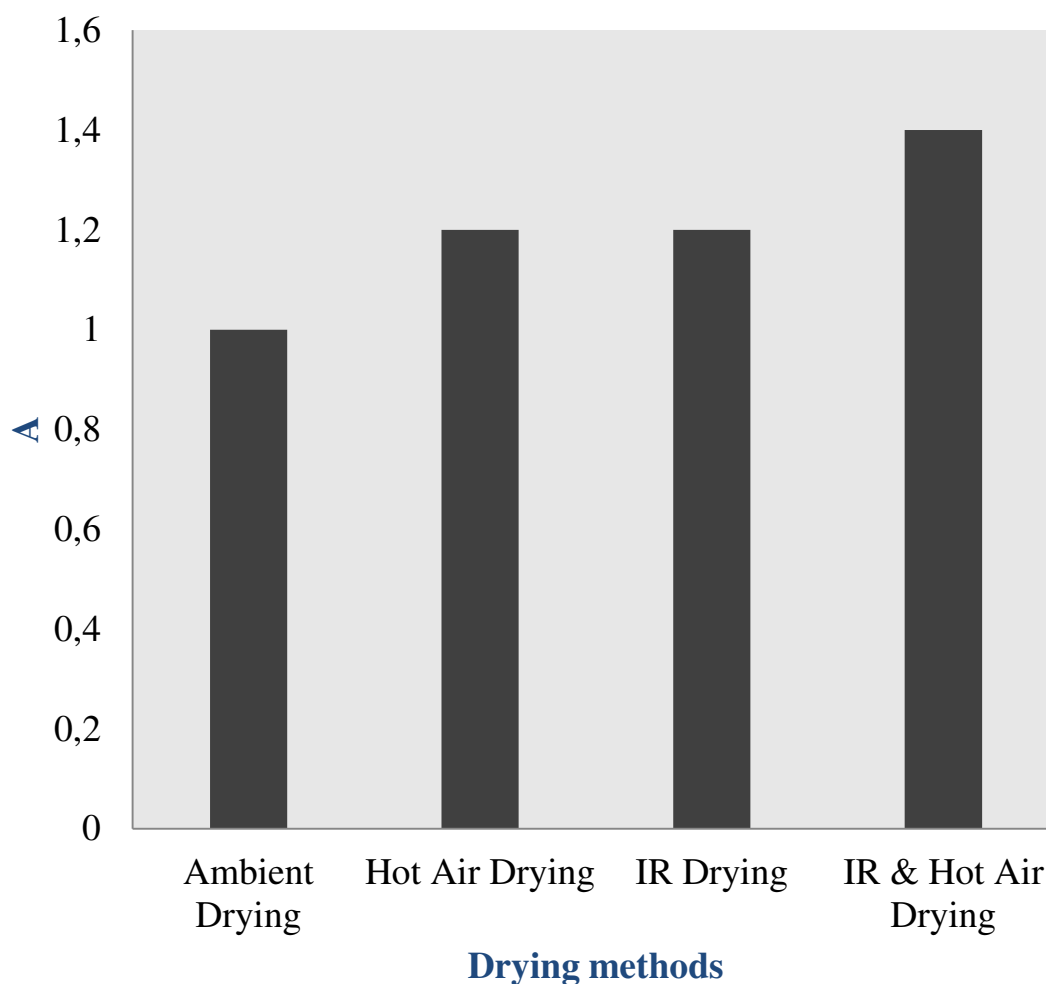


Fig: 5.7: Drying methods on 'A' of the edible films

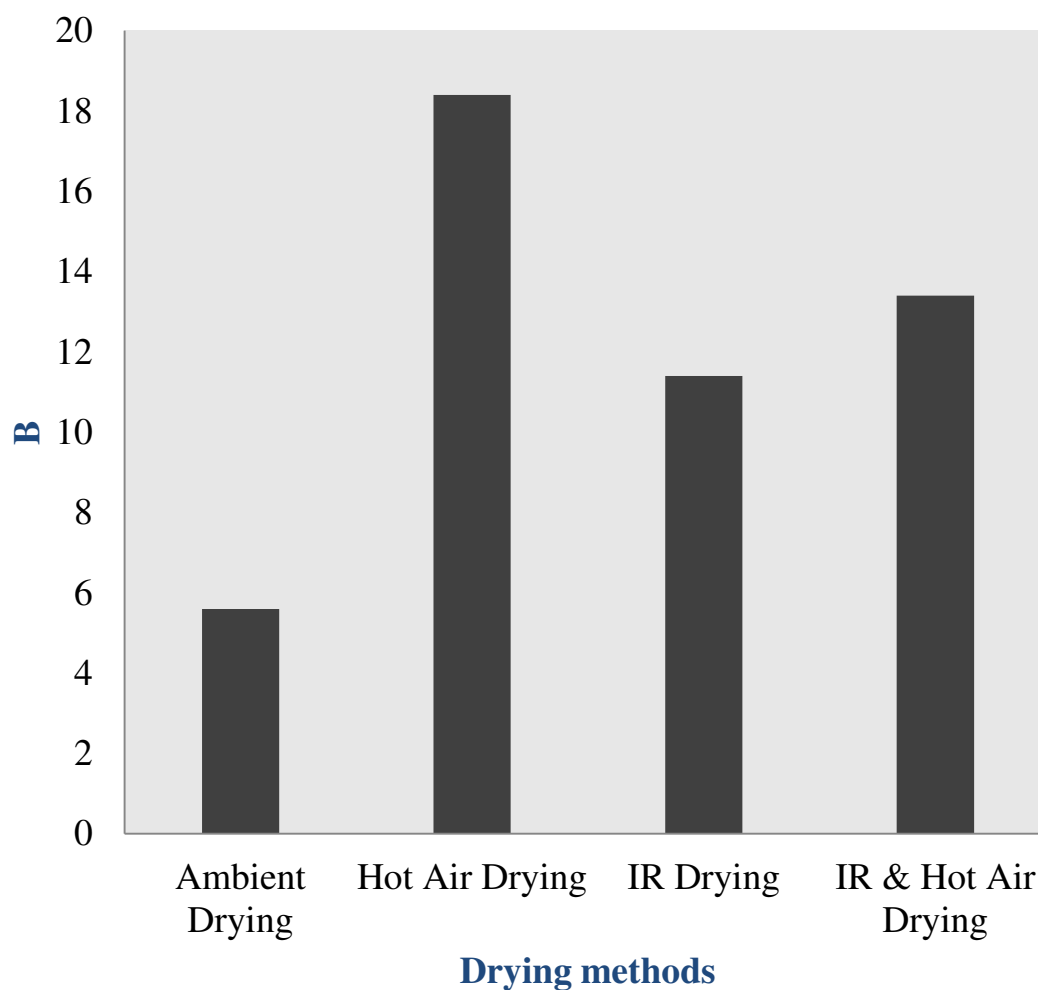


Fig: 5.8: Drying methods on 'B' of the edible films

From Fig. 5.7., it was found that there was no significant difference in 'A' colour parameter of the bionanocomposite films due to the drying methods. Despite insignificant difference, as the drying temperature increased, there was a positive increase in the 'A' value indicating a slight redness in the bionanocomposite films. This could be because of the browning effect due to higher drying temperatures.

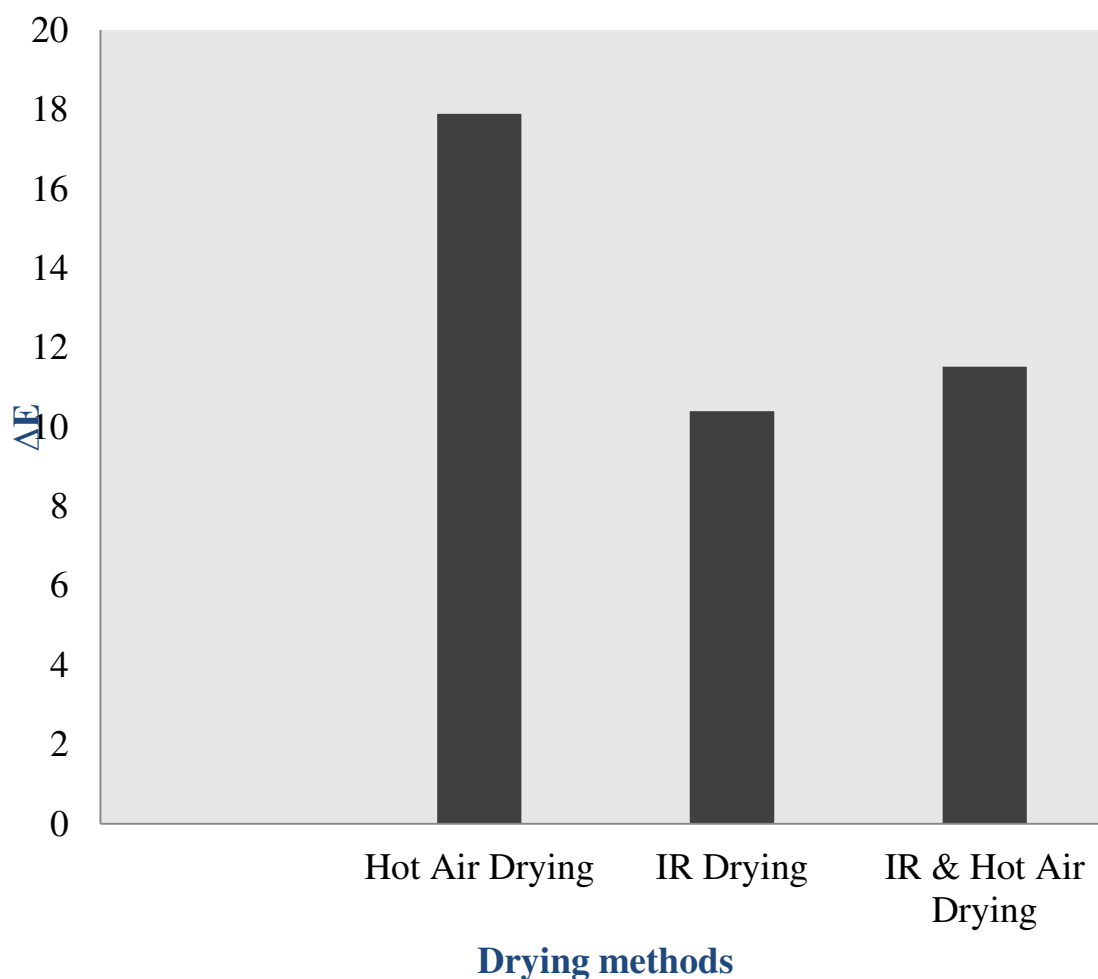


Fig: 5.9: Drying methods on ' ΔE ' of the edible films

From Fig. 5.8., it is found that the 'B' of the bionanocomposites increased with the increase in drying temperature and higher drying rate. This means that, the yellowness of the films increases as the drying temperature increased. The yellowness of the hot air dried films was found to be highest among the rest. The films dried in ambient air were found to be more transparent than the films dried in hot air. In oven drying, the drying occurred in the surface layers of the film forming solution, and this kind of preferential drying of surface layers could be attributed to Maillard reaction products. The hot air in the oven drying could make the films become more yellowish or brownish (Srinivasa et al., 2004). As a result, 'b' values of hot air dried films were found to be higher than IR drying as well as ambient drying. On the other hand, in the case of IR drying, the electromagnetic waves could penetrate deep inside the film forming and remove the moisture mass from

inside out (Srinivasa et al., 2004). Therefore, the yellowness of the IR dried films were relatively lower as compared to hot air dried films.

Fig. 5.9. shows the effects of drying methods on the change in film colour of the bionanocomposite films dried using hot air drying, IR drying and IR plus hot air drying. The results showed that the colour change was higher in the case of hot air drying, indicating that the hot air drying had significantly changed the film colour than other drying methods. It showed that the surface browning was higher in the case of hot air drying. The IR drying was showing the lower colour change, mainly due to the core heating. IR plus hot air drying provided the colour change which was in between the hot air drying and IR drying.

CHAPTER 6

CONCLUSION

In this work, we carried out to explore the effects of drying methods on the film properties of bio nanocomposite edible films. The films were prepared using solution casting method. Based on the test results of WVTR, tensile properties and film colour parameters, the following conclusions are drawn. In order to understand the effects of drying methods, four drying methods, namely, (1) ambient drying, (2) hot air drying, (3) IR drying, and (4) IR plus hot air drying, were considered in the research work. Ambient drying, hot air drying, IR drying and IR plus hot air drying methods could dry the films in 36h, 8 h, 3 h and 2 h, respectively. IR plus hot air drying and IR drying methods could exhibit lower WVTR as compared to ambient drying and hot air drying. IR plus hot air dried films showed the highest TS (26.26 ± 0.41 MPa) and TM (48.54 ± 0.38 MPa) with reduced film flexibility among the four drying methods. Because higher drying temperatures could form the maillard reaction products, the films became slightly darker and yellowish. The lowest colour change was observed in both IR drying and IR plus hot air drying based films. Among the four drying methods, IR plus hot air drying was considered as a faster drying method that can form the edible films in 2 hours. However, literatures showed that the edible films can be produced even faster. For example, microwave drying could dry the films in less than 5 min.

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