MODIFIED ATMOSPHERE STORAGE OF GINGER RHIZOME USING SILICONE-BASED MEMBRANE SYSTEM UNDER AMBIENT TEMPERATURE CONDITIONS

PRIYANKA KAMAT

Department of Bioresource Engineering

Faculty of Agricultural and Environmental Sciences

McGill University

Sainte-Anne-de-Bellevue, Quebec, Canada

July 2016

Thesis submitted to McGill University in partial fulfilment of the

requirement of the degree of

Master of Science

In

Bioresource Engineering

ABSTRACT

Providing food security to people all over the world has become an important challenge for the scientists and the policy makers alike. In many areas of the world, the production and supply of food to the population is challenging, while the other areas face issues like food wastage due to the lack of proper conditions and planning for postharvest storage. The modified atmosphere storage is a technique for the storage of fresh fruits and vegetables, for a longer period of time under ideal storage conditions. In such systems, the external parameters like temperature, pressure, relative humidity (RH), and the atmospheric gas concentrations are manipulated and modified to create optimum storage conditions. The optimum conditions for storage vary depending on the product stored, hence studying the storage of various types of produce is absolutely essential. Membrane-based storage systems are a type of modified atmosphere storage system, involving the use of silicone-based membranes.

This study investigates use of membrane system for improving the storage life of ginger rhizome. The first part of this thesis describes the characterisation and selection of membrane for use in storage. This comprises studying the physical and mechanical parameters of the silicone-based membranes including three commercially available membranes (GA, GB and GC) and two reference membranes (MSM and CSM). The permeability of the membrane and its selectivity ratio for the carbon dioxide gas remain as the main requirement for selection of membrane for food storage. Based on the preliminary studies, the MSM, CSM, and GC membranes were selected for investigating their application in ginger storage.

The second phase of the study included ginger storage in the membrane-based system for prolonging the storage life while maintaining the visual appearance of the ginger to a desired level. The response surface methodology with two factors viz. duration of storage and membrane area was used to find the proper storage conditions for ginger. The investigated duration of storage ranged between 7 to 21 days with membranes of different surface areas providing an interface between the ambient air and the air in the storage container. Parameters like firmness, color difference, percent mass change, and total phenolic content of the ginger were measured before and after its storage. The change in oxygen concentration in the storage chamber and the respiration rate were decreased till the 7th day of storage and after which it remained steady until the 21st day

of storage. Low oxygen concentration and high carbon dioxide concentration are desired in the modified atmosphere storage systems to slow down the metabolic activities and respiration rate. The results were similar when the GC and the MSM membranes were used for the storage of ginger. During the trials, the storage conditions have helped maintain the firmness of ginger roots while minimizing mass loss. Although no significant differences in the final content of total phenolic compounds were observed between the different membranes used, the contents decreased during storage. Significant differences in skin color were observed between the different membranes used. MSM and GC membranes had similar results. Unfortunately, at the end of the storage trials, ginger rhizomes stored under modified atmospheres were no longer marketable since they all started to bud. Further studies are required to optimize the silicone membrane system and storage conditions for the long term conservation of fresh ginger rhizomes.

RÉSUMÉ

Assurer la sécurité alimentaire partout dans le monde est un défi important pour les scientifiques et les décideurs politiques. Dans plusieurs régions, la production et l’approvisionnement de nourriture de qualité sont difficiles, tandis que dans d’autres, les pertes d’aliment sont importantes dus à l'absence de conditionnement post-récolte et au manque de planification pour le stockage des produits fraîchement récoltés. L’entreposage sous atmosphère modifiée est une technique qui permet d’accroître la durée de conservation des fruits et des légumes frais. Cette technique permet de contrôler la température, l'humidité relative (HR), et la concentration de gaz afin de créer les conditions optimales pour la conservation des produits frais. Il est essentiel d’effectuer des études pour définir les conditions optimales d’entreposage puisque ces dernières varient en fonction de la nature du produit. De plus, des études sont nécessaires pour développer de nouvelles technologies qui permettent d’obtenir et de maintenir les conditions requises.

Cette étude porte sur le développement d’un système utilisant des membranes à base de silicone pour contrôles la composition des gaz pour l’entreposage des rhizomes de gingembre frais sous atmosphère modifiée. Dans un premier temps, cinq différents modèles de membranes disponibles commercialement (identifiées comme GA, GB, GC, MSM et CSM) ont été caractérisées afin d’identifier celles qui seraient le mieux adaptées pour la conservation sous atmosphère modifiée. Les caractéristiques mesurées étaient les propriétés physiques et mécaniques, les perméabilités aux gaz et le rapport de sélectivité dioxyde de carbone : oxygène. Les résultats ont indiqué que les membranes GC, MSM et CSM avaient les propriétés requises pour être utilisées dans les systèmes à atmosphère modifiée.

Dans un deuxième temps, l'étude a porté sur des essais de conservation sous atmosphère modifiée de rhizomes de gingembre en utilisant les membranes sélectionnées. La méthodologie de surface de réponses à deux facteurs a été utilisée pour comparer les essais. Les facteurs étudiés étaient la concentration visée en oxygène et la durée d’entreposage, et les critères de qualité mesurés étaient la fermeté, la couleur, la perte de poids et la teneur totale phénolique des rhizomes de gingembre. Il est généralement reconnu qu’une diminution de la concentration en oxygène accompagnée d’une augmentation de la concentration dioxyde de carbone permet de ralentir

l'activité métabolique entrainant une augmentation de la durée de l'entreposage. Les résultats ont indiqué que l'oxygène dans la chambre à atmosphère modifiée et l'intensité respiration des rhizomes diminuaient jusqu'au septième jour et après quoi il est demeuré relativement stable jusqu'au 21e jour de stockage. Lors des essais, les conditions maintenues ont permis de maintenir la fermeté du gingembre tout en minimisant les pertes de poids. Quoi qu'il n'y eût pas de différences significatives dans la teneur en composés phénoliques totaux entre les différentes membranes utilisées, les taux avaient diminué durant l'entreposage. Des différences significatives de la couleur de la pelure ont été observés entre les différentes membranes utilisées. Les membranes MSM et GC ont données des résultats similaires. Malheureusement, à la fin des essais, les rhizomes de gingembre entreposés sous atmosphère modifiée n'étaient plus commercialisables puisqu'ils avaient tous commencer à bourgeonner. Des études supplémentaires sont requises pour optimiser le système utilisant les membranes de silicone pour la conservation des rhizomes de gingembre frais.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisor and guide, Dr. Vijaya Raghavan, for giving me this great opportunity to work in his lab and providing me with the resources and facilities without which this project wouldn't have been possible. It was an honour working with my fellow lab mates under Dr. Raghavan's supervision.

My unequivocal thanks to Mr. Yvan Gariépy, without whom the completion of the project wouldn't have been possible. His technical know-how and practical knowledge of the subject helped me throughout the project. I appreciate the conversations I had with Dr. Darwin Lyew, and thank him for his counsel.

Further, my gratitude goes to my former and present teammates for their kind words and support: Sai Kranthi, Brinda, Xue Hu (Christina), Lanrewaju, Amanat, and Ademola. I extend my appreciation to my friends from the Bioresource Department, Shrestha, Agneev, Na Ni, Zhanghu Jia with whom I shared the lab while working on this project.

Throughout this journey, there have been people who have motivated me to move forward and I would like to offer my appreciation to them. I am extremely grateful to my friends, Nureen, Sukhman, Shreyasi, Dalia, Girija, Usha, Reshmi, Kamaljit, Yadnyavalkya, Snehal, Pooja, Surabhi, Rucha, Akhil, Chaitanya, and Ateen for their support and encouragement.

Lastly, I wouldn't have made it here without the support and love of my parents (Mr. Rajendra Kamat & Mrs. Vedangi Kamat). It is through their hard work and motivation that I am able to follow my dreams. I would like to thank my sister (Ms. Rajeshwari Kamat) who has always been there for me. My gratitude goes to extended family and friends who have encouraged me and cared for me throughout. I would like to dedicate this thesis to my late paternal grandfather (Mr. Wamanrao Kamat) and my late maternal grandfather (Mr. Atchutanand Kamat Bambolkar). You shall always be remembered.

CONTRIBUTION OF THE AUTHORS

The work in this thesis was performed by Ms. Priyanka Kamat under the guidance of Dr. Vijaya Raghavan of the Department of Bioresource Engineering, Macdonald campus, McGill University, Montreal. The entire work was carried out Postharvest Laboratory, Macdonald Stewart building, at the Macdonald campus.

The following are manuscripts prepared and to be submitted for publication:

1) Priyanka Kamat, Yvan Gariépy, Jiby Kurian, Vijaya Raghavan (2016) “Characterization of silicone-based membrane for modified atmosphere storage application”

2) Priyanka Kamat, Yvan Gariépy, Jiby Kurian, Vijaya Raghavan (2016) “Storage life enhancement of ginger using silicone membrane system under ambient temperature storage conditions”

Co-authors, Dr. Raghavan provided the scientific suggestions in the development of the manuscripts. Dr. Kurian from the Department of Bioresource Engineering was involved in editing of the manuscripts. Mr. Gariépy from the Department of Bioresource Engineering provided the technical suggestions and facilities for carrying out the experiments.

Table of Contents

List of Figures

List of Tables

CHAPTER I

GENERAL INTRODUCTION

Food is a basic necessity for human survival and the uncontaminated food in good conditions should be available to everyone. Some of the developing countries find it challenging to provide this basic requirement due to socio-economic problems. The production of food has improved in the recent years, yet the attempts to make sure this produced food available have been greatly unsuccessful. In the western countries, various storage techniques have been devised which help in preservation and storage of crop produce in good condition.

Food security has always been a major concern for the world. International bodies like Food and Agricultural Organisation (FAO) are constantly working to improve the agricultural practices to eliminate hunger, food insecurity and malnutrition. Factors like rural poverty, inefficient agricultural practices, and poor economic conditions lead to substantial wastage of crop. Also, with an increase in world population, which is expected to reach 9.6 billion by the year 2050, food safety and food security have become the need and necessity of the hour (Hubert, Rosegrant, van Boekel, & Ortiz, 2010; UN-News, 2013).

Postharvest losses are considered the main culprit of food losses and wastage. Kader (2004) estimated that about one-third of the food production goes to waste and isn't consumed at all (Kader, 2004). Most of the food losses occur in the tropical regions, with fruits and vegetables including but not limited to tomatoes, bananas, citrus fruits, berries, and many seasonal fruits, with losses ranging from 1 to 50 % of the production (Morris, 1978). Avoiding these losses may appear like a simple task, but various factors are to be considered. These include agricultural practices, economic status, food trade, sex-age distribution in the country viz. available manpower for agriculture, undernourishment in the population, and the government policies (FAO, 2013). A significant volume of research and developing the improved know-how of the practical trading aspects of a particular fruit can lead to better handling, transport, storage, and distribution of the fruit so that it reaches the consumer at a fair cost. Advanced horticultural practices and modified cultivars of the fruits has lead to higher yield and reducing losses of fruits in the field (Forero, 2007). Though the crop cultivation practices have improved, it has been a struggle to maintain the quality of the produces. It is necessary to store produce under proper conditions so it remains acceptable for consumption after a long period of time. Three aspects of the post-harvest practices: handling, transport, and storage are key in avoiding food losses. In the countries like Canada and the USA, importing of food materials has leads to higher-cost of fruits and vegetables during the non-producing months, hence storage is a preferred option for retailers and farmers in these countries (Gariepy & Raghavan, 1989). Fresh ginger is an important crop produce importing into Canada and the USA because of its culinary and pharmaceutical uses.

Ginger is a rhizome that grows in sub-tropical countries in Asia and has been used as a spice in cooking; for making pickles, digestive drinks, candy, and ginger wine; and in herbal medicines. It also has biopharmaceuticals applications for ameliorating colonic tumor (therapeutic use not prophylactic) (Abd Allah, Makboul, & Mohamed, 2016), treating IgE-mediated allergic disorders (e.g. Allergic rhinitis) (Kawamoto et al., 2016) and reducing the ill effects of high-fat diet induced obesity (Misawa et al., 2015). Ginger is produced as a cash crop and has a gradually increasing demand in the global market due to its various uses. Since ginger is a perennial crop, the postharvest storage of ginger to avoid losses due to spoilage is a necessity.

Perishables like fruits and vegetables, which are produced in bulk, should be carefully harvested, handled, transported and properly stored according to the specific requirements of gas concentrations, temperature and relative humidity (RH). Since the ambient temperatures and humidity in the tropical countries are not suitable for long-term storage of fresh fruits and vegetables, decay often sets in leading to spoilage of food materials (Forero, 2007). Low-temperature storage provides a convenient way to extend shelf life by decreasing the metabolic activities of the fruits and vegetables as well as inhibiting the growth of pests and harmful microbes (Riad, 2004). Commonly, low temperature with the regular atmosphere (RA), low temperature with RA and high RH atmosphere (HRA) and low temperature with high RH and modified/controlled atmosphere (MA/CA) storage are used for the storage of fresh fruits and vegetables (Naik, Ambrose, Raghavan, & Annamalai, 2014).

Modified atmosphere storage (MAS) provides a solution and is being used since the last century to store perishable fruits and vegetables (Vigneault, Canada, Agriculture, & Agri-Food, 1994). By increasing the CO_2 levels and decreasing the O_2 levels for CA and MA storage, ethylene production rate and the respiration rate are slow down to maximize the shelf life of the stored fresh food materials (Kader, Zagory, & Kerbel, 1989), hence reducing the losses and maintaining product quality (Farber et al., 2003). Postharvest storage of ginger at lower temperatures of 10-15 °C helps store ginger for a long duration of time. However, the MAS hasn't been studied for the storage of fresh ginger and needs to be explored to optimize the storage conditions to maintain the quality of the stored ginger.

1.1 Hypothesis

Food security is a major concern for today's society, controlled atmosphere storage provides an avenue to avoid food wastage and improve the shelf-life of fresh crop produces. The conventional storage methods need to be modified in order to achieve a longer period of storage and to maintain the quality of fruits and vegetables. Thus, applying the modified atmosphere storage technique for the storage of a perishable product will help extend its storage life while retaining the characteristics present at the time of its harvest.

1.2 Objectives

1.2.1 Overall Objective

The overall objective of this study was to design, fabricate and test a hermetic storage container for the modified atmosphere storage of ginger. The critical point of the system is the silicone membrane of a specific area that provides an interface between the inner atmosphere of the container and the ambient outside. The membrane has to be selected and the area of the selected membrane and the storage time are to be determined for optimal storage of ginger in a modified atmosphere.

1.2.2 Specific Objectives

1) To examine the physical and mechanical properties of the different types of silicone membranes available, and selection of membrane for further studies.
2) To assess the modified atmosphere storage of ginger stored in a sealed container with silicone membrane for gas permeation and evaluate the performance of the system using different areas of the silicone membrane and storage time under ambient conditions.

References

Abd Allah, E. S. H., Makboul, R., & Mohamed, A. O. (2016). Role of serotonin and nuclear factor-kappa B in the ameliorative effect of ginger on acetic acid-induced colitis. *Pathophysiology, 23*(1), 35-42. doi:10.1016/j.pathophys.2015.12.001

FAO (2013). The State of Food Insecurity in the World 2013. http://www.fao.org/docrep/018/i3434e/i3434e00.htm [last accessed on 13 July 2016].

Farber, J. N., Harris, L. J., Parish, M. E., et al. (2003). Microbiological Safety of Controlled and Modified Atmosphere Packaging of Fresh and Fresh-Cut Produce. *Comprehensive Reviews in Food Science and Food Safety, 2*, 142-160. doi:10.1111/j.1541-4337.2003.tb00032.x

Forero, M. P. (2007). *Storage life enhancement of avocado fruits.* (Master's Dissertation), McGill University.

Gariepy, Y., & Raghavan, G. S. V. (1989) A mathematical model for a pressure regulated silicone membrane gas permeator for CA storage. *Paper - American Society of Agricultural Engineers; 1989. (89-4049):16 pp. 16*

Hubert, B., Rosegrant, M., van Boekel, M. A. J. S., et al. (2010). The Future of Food: Scenarios for 2050. *Crop Science, 50*(Supplement_1), S-33-S-50. doi:10.2135/cropsci2009.09.0530

Kader, A. A. (2004). Increasing food availability by reducing postharvest losses of fresh produce. Paper presented at the V International Postharvest Symposium 682.

Kader, A. A., Zagory, D., & Kerbel, E. L. (1989). Modified atmosphere packaging of fruits and vegetables. *Critical Reviews in Food Science and Nutrition, 28*(1), 1-30. doi:10.1080/10408398909527506

Kawamoto, Y., Ueno, Y., Nakahashi, E., et al. (2016). Prevention of allergic rhinitis by ginger and the molecular basis of immunosuppression by 6-gingerol through T cell inactivation. *The Journal of Nutritional Biochemistry, 27*, 112-122. doi:10.1016/j.jnutbio.2015.08.025

Misawa, K., Hashizume, K., Yamamoto, M., et al. (2015). Ginger extract prevents high-fat diet-induced obesity in mice via activation of the peroxisome proliferator-activated receptor δ pathway. *The Journal of Nutritional Biochemistry, 26*(10), 1058-1067. doi:10.1016/j.jnutbio.2015.04.014

Morris, R. F. (1978). *Postharvest food losses in developing countries: a bibliography*: National Academies.

Naik, R., Ambrose, D. C. P., Raghavan, G. S. V., et al. (2014). Enhancing shelf life of minimally processed multiplier onion using silicone membrane. *Journal of Food Science and Technology-Mysore, 51*(12), 3963-3969. doi:10.1007/s13197-012-0898-2

Pinstrup-Andersen, P. (2009). Food security: definition and measurement. *Food Security, 1*(1), 5-7. doi:10.1007/s12571-008-0002-y

Riad, G. (2004). *Atmosphere modification to control quality deterioration during storage of fresh sweetcorn cobs and fresh-cut kernels.* (3146245 Ph.D.), University of Florida, Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Vigneault, C., Canada, Agriculture, & Agri-Food, C. (1994). *Techniques for controlled atmosphere storage of fruits and vegetables*. [Ottawa]: Research Branch, Agriculture and Agri-Food Canada.

CHAPTER II

LITERATURE REVIEW

2 Introduction

Ginger is one of the essential spices in the world, prevalently grown in Asian countries with tropical and sub-tropical climate. The ginger (*Zingiber officinale*) rhizome grows underground, is irregular shaped, branched or palmate and is often used as a spice in cooking or is pickled (Britannica, 2016; Gross et al., 2014). Ancient Chinese and Indian medicine advocates the use of ginger for various ailments including stomach aches, nausea, diarrhea and as dietary supplements for treating cold and flu (Kaur et al., 2015; National Center for Complementary and Alternative medicine, 2008). Various scientific studies have explained the effect of ginger in the treatment of breast cancer, pancreatic cancer, liver cancer, urinary bladder cancer (Baliga et al., 2011). Uses of the extracts and essential oils from ginger have been investigated for treating arthritis (Funk et al., 2016) and fat-diet-diet induced obesity in mice (Misawa et al., 2015). Ginger is originated in the Southeast Asia where it was first grown and due to the ease of transportation as a viable tuber, its cultivation and use has spread worldwide. The top five countries producing ginger, and the percent of their contributions to the annual world production, include India (34.6 %), China (19.1 %), Nepal (10.6 %), Nigeria (7.8 %), and Thailand (7.5 %) (Food & Agriculture Organization of the United, 2014).

Healthy harvested ginger has a knobby, fibrous form and yellowish-brown appearance. Desirable quality characters include yellowish-brown skin color, plump tuber, smooth skin without bruising or pest damage and absence of vegetative sprouts (Gross et al., 2014). The ginger plant grows for a duration of 6 to 12 months after which it is harvested and sold as black ginger by scalding or white ginger by scraping and washing (Plotto, 2002). Harvested ginger needs to be stored at cooler temperatures to avoid water loss by respiration and transpiration (Planella & Seepersad, 1990). As time passes, the skin starts losing its sheen and gains a dry-rough appearance. To avoid this, the RH needs to be maintained in the range of 85-90 % (Gross et al., 2014; National Center for Complementary & Alternative Medicine, 2008).

2.1 Chemical composition of ginger rhizome

Natarajan et al. (1972) studied twenty-six varieties of ginger and determined chemical composition of rhizomes as follows: essential oil (1 to 2.7 %), acetone extract (3.9 to 9.3 %), crude fiber (4.8 to 9.8 %), and starch (40.4 to 59 %) (Natarajan et al., 1972).

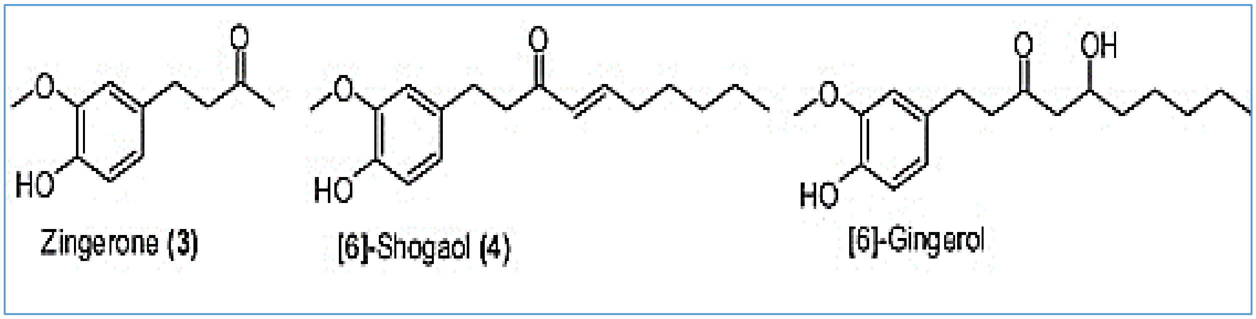

*Fig. 1: Chemical structure of zingerone, gingerol and shogaol (Kumar, Murthy, & Bettadaiah, 2014)**

The chief pharmacological activity of ginger is due to the compounds such as gingerol, shogaol and the related paradols. The concentration of the volatile and non-volatile contents in ginger is dependent on the time of harvest, the quality of soil and cultivar used (Ali et al., 2008). The raw pungent taste of ginger can be ascribed to non-volatiles comprising of oleoresin (gingerols, shogaols, paradols, and zingerone) (Jakribettu et al., 2016). A number of other biologically active phytochemicals are also present in fresh ginger and their quantity is dependent on the location of cultivation, rhizome maturity at harvest, and the method of extraction of these compounds. The essential oils present in the ginger impart the specific aroma to the rhizome and is comprised of the various compounds presented in Fig. 1 and Fig. 2.

Limonene is listed as a flavouring agent and it has been researched for its potency in treating preclinical mammary and liver cancers (Lopresto et al., 2014). Linalool is a monoterpene used in the production of shampoo scents, detergent fragrance, drug formulations, and it has been studied for application in treating spatial memory impairment in transgenic Alzheimer’s mice (Letizia et al., 2003; Sabogal-Guáqueta et al., 2016). Terpinene, borneol, camphene and other compounds present in the ginger essential oils have been investigated for their use as anti-microbial agents, flavoring agents, and in food packaging applications as bio-nano-composites.

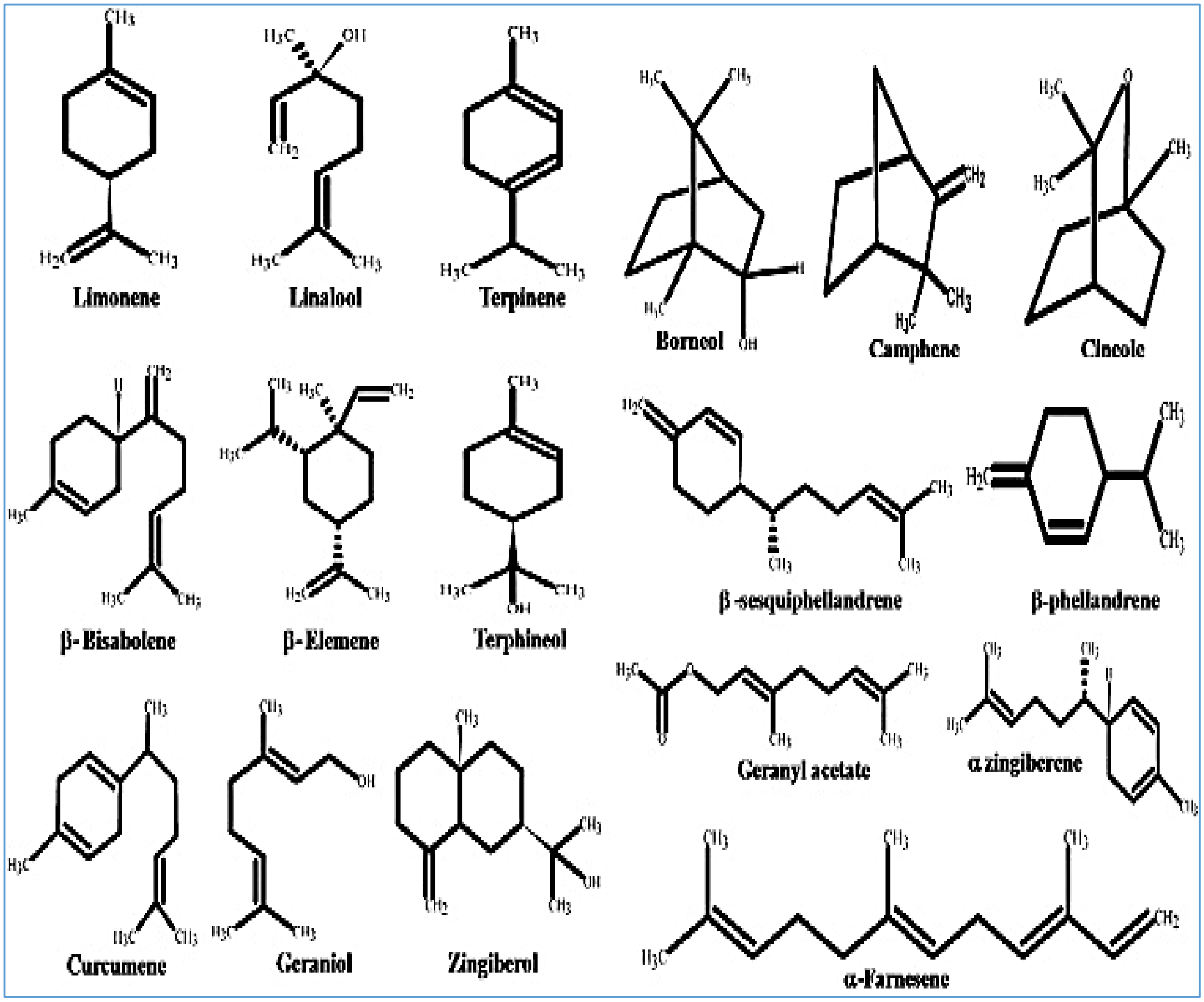

*Fig. 2: Important phytochemicals in ginger oil**

* Reprinted from *Essential Oils in Food Preservation, Flavor and Safety*, Jakribettu et al., Chapter 50 - Ginger (Zingiber officinale Rosc.) Oils, 447-454, (2016), with permission from Baliga M. S. (San Diego Academic Press).

- **Ginger products**

2.1.1 Primary products:

Demand for fresh ginger has steadily been increased over the years. Fresh ginger is harvested, washed and dried in the sun and consumed after treatment to kill pathogens. Canada imports most of its fresh ginger from China, India, Hawaii, Brazil and Central America (StatsCanada, 2013).

*Fig. 3: Fresh ginger**

*Licensed for reuse from https://www.pixabay.com/

Dried ginger quality and type depends on the country from which it is imported. Jamaican ginger is of high quality with light color and subtle flavor. Indian ginger has reddish-brown color with a delicate flavor and is dried after washing with skin or lightly scraped. Chinese dried ginger can be whole peeled, or sliced unpeeled. It is more fibrous, bitter and lighter colored than Indian ginger.

*Fig. 4: Dried ginger**

* Reprinted from The Invaluable Medicinal Spice Crops, *Chapter 23*, Prabhakaran Nair, The Agronomy and Economy of Turmeric and Ginger, 433-452, 2013, with permission from Elsevier.

Different drying techniques including solar hybrid drying (Prasad et al., 2005), vacuum drying (Gümüşay et al., 2015), radio-frequency drying, microwave-convective drying (Śledź et al., 2013) have been studied for the drying of ginger. Kejing et al. (2016) studied different types of drying methods and their effects in terms of drying time, changes in volatile contents, and anti-oxidant activity. They concluded that the use of intermittent microwave with convective drying gave the best results in terms of energy consumption, drying time, and the retention of volatiles and anti-oxidant activity (An et al., 2016).

*Table 1: Drying time, energy consumption and yield of extraction as reported by (An et al., 2016)**

Drying methods	AD	IR	FD	MD	IM&CD
Drying time (h)	12.0 ± 0.5	6.0 ± 0.7	44.5 ± 2.0	1.8 ± 0.3	1.5 ± 0.2
Energy consumption (kW h/g H_2O)	3.30 ± 0.08	12.23 ± 0.24	33.7 ± 0.53	2.7 ± 0.12	3.21 ± 0.1
Extraction yield (ml/g %)	2.69 ± 0.32	2.58 ± 0.19	3.55 ± 0.22	2.97 ± 0.65	3.35 ± 0.55

Where AD = hot air drying, IR = infrared drying, FD = freeze drying, MD = microwave drying, and IM & CD = intermittent microwave-convective drying.

* Reprinted from Food Chemistry, *Vol 197*, An et al., Comparison of different drying methods on Chinese ginger (*Zingiber officinale Roscoe*): Changes in volatiles, chemical profile, antioxidant properties, and microstructure, 1292-1300, 2016, with permission from Elsevier.

2.1.2 Secondary products

Preservation of ginger by pickling or in brine or in syrups has been traditionally done using less fibrous and less hot ginger roots which have been harvested early (Nair, 2013). Following methods are used for preservation of ginger:

- Ginger in brine or in syrup: Tender rhizomes are brined for the preparation of pickles and sauces. Brined ginger is boiled in water to remove the salt and then preserve it in sweet syrup for production of jam (Wolf, 2016) and ginger candy, which is a major industry in Australia (Plotto, 2002).
- Ginger paste and ginger puree: For the preparation of ginger puree, fresh ginger is peeled, washed, sanitized, cooked briefly, and pulverized. Ginger paste is preparing by salting and seasoning of the grinded ginger. The commercial ginger paste products contain additives like salt, oil, vinegar, and permitted preservatives.
- Culinary preparations: Gingerbread, ginger based cookies, ginger cakes, ginger biscuits, and marmalades.
- Ginger drinks: Ginger tea, ginger wine, ginger ale, and ginger syrups (for sweet drinks)

2.2 Harvest and Postharvest methods

- **Harvest**

After planting the ginger rhizome, the time of harvest for the matured ginger depends on the post process use. The desired levels of three contents in the final products determine the harvesting time; the fiber, the volatile oil content and the pungency of taste (Sutarno, 1999; Weiss, 2002). Depending on the end use of ginger following its harvest, the level of these three helps to decide whether to harvest a crop at a specific time or wait longer. After about 8 months of cultivation, the leaves of ginger plants turn yellow and eventually dry out. Using a spade or forked rake, the root clumps are carefully picked up. The rhizomes are then separated from the dried leaves, roots, and the adhered soil.

Table 2: Harvest time of ginger based on the postharvest use adapted from Ginger Postharvest operations (Plotto, 2002)

Postharvest use	Best harvest time
Direct consumption as fresh ginger	5 months
Dried ginger	8-9 months, leaves start yellowing
Preserved ginger	5-7 months
Extracting for essential oils	8-9 months

- **Washing, sanitization, and drying**

Washing of rhizomes can be done manually with stagnant water but jet pressured washing of the ginger is preferred since it helps eliminate all dirt adhered to it and reduces the microbial load significantly. Boiling the rhizomes by immersing in water for 10 min. can further reduce the microbial load and terminates the enzymatic processes (Sutarno, 1999). After this ginger rhizome is peeled using either chemical peeling or mechanical peeling (Nair, 2013). Peeling helps in the reduction of drying time.

Traditionally, the ginger is washed and soaked in water, steeped in calcium oxide solution to bleach, dried for a week in the sun, steeped in calcium oxide again followed by final drying (Pruthi, 1976). Moisture content of ginger after drying should be between 8 to 10 % and not more than 12 % (Govindarajan, 1982). Expected weight loss in drying is about 60 to 70 % (Weiss, 2002). Drying of ginger in multiple stages helps in retaining the oleoresin and essential oil content.

- **Grading**

The AGMARK (India) and ASTA provide with guidelines and specifications for grading and sorting of ginger for trade. The various categories include garbled non-bleached ginger (whole), ungarbled non-bleached ginger (whole), garbled bleached ginger (whole), ungarbled non-bleached ginger (whole), and ginger powder (AGMARK, 2005). It is not legally mandatory to adhere to the specifications provided but it is a sign of the quality product. The minimum size of rhizomes for trade according to Indian Standard Specifications (ISS) is 20 mm (ISS, 2008). The ginger, whole or ground, should be free from any visible molds and insect infestation.

- **Storage**

Fresh ginger needs to be stored in a cool and humid environment. Ginger rhizomes are traded, in fresh or dry form, all over the world. From the time of harvest to the time of sale, it needs to be stored in an environment which maintains its quality for consumption. Premature harvest and delayed harvest can lead to greater postharvest losses. Generally, it is advised that mature ginger rhizomes be stored for 2 to 3 months, at cooler temperatures ranging 12 to 14 °C with the RH between 85 to 90 % (Chen, 2014) because storage at this temperature range reduces the chilling injury and moisture loss. Akamine (1977) observed that storage of ginger at 13 °C with 65 % RH lead to dehydration and wilting of the ginger rhizome (Akamine, 1977).

Ginger rhizomes are prone to sprouting, mold growth, physiological breakdown, shriveling due to desiccation, and softened with discolored appearance during storage (Yusof, 1990). High humidity leads to sprouting, fibrous roots, discoloration, and decay; hence storing in polythene bags is avoided (Afek & Kays, 2004). Since maintaining the required storage conditions isn't economically feasible for the farmers, ginger rhizomes are stored in underground tunnels or in sand where the temperature and relative humidity (RH) are maintained, but this leads to loss of ginger by spoilage (Kim & Lee, 2006). Ginger rhizomes also have a chilling sensitivity which may cause pitting of skin and color change (Chen, 2014).

Water loss from ginger rhizome leads to shriveled appearance, fibrous roots and decreases the overall quality. Low RH leads to moisture loss, whereas high RH causes pathogen attack. Coating of ginger with a waxy substance doesn't delay the water loss and the use of polythene bags leads to decay due to higher RH. Similarly, cutting of ginger rhizome leads to higher moisture loss from it and hence curing of ginger is necessary to extend its shelf-life (Afek et al., 2004; Akamine, 1977).

Sprouting during storage is another problem that needs to be addressed. Ionizing (gamma or X-ray) irradiation has shown to inhibit sprouting when applied in moderation (Mukherjee, Thomas, & Raghu, 1995; Yusof, 1990). Mukherjee et al. (1995) demonstrated that gamma irradiation of 60 Gy prevented sprouting and rooting, additionally when combined with a treatment of Trichoderma prolonged the shelf life of the treated ginger stored in polyethylene bags (Mukherjee et al., 1995). The pre-harvest treatment with maleic hydrazide and CIPC (chlorpropham) pro-actively reduced the sprouting in ginger (Mukherjee et al., 1995; Paull, Chen, & Goo, 1988a). Chung et al. (2011) reported the use of perforated LDPE bags for storage of ginger rhizomes, to constrain the rotting while preserving color, flesh firmness, pH, and sensory characteristics of ginger rhizomes (Chung & Moon, 2011).

2.3 Ginger Production and Postharvest pathology

Ginger has been used for many centuries because of its anti-inflammatory, anti-fungal (Le et al., 2014; Touba et al., 2012), and anti-microbial properties (Park et al., 2008; Shaista, 2010) for many centuries. Regardless, ginger can be attacked by numerous plant pathogens such as bacteria, viruses and fungi (Le et al., 2014). This can lead to a loss in crop yield and severe economic difficulties for farmers in the developing countries where ginger is mostly cultivated. During cultivation, the occurrence of plant diseases like Pythium soft rot (PSR) were first documented by Butler (1907) more than hundred years ago (Butler, 1907; Le et al., 2014). Moreover, the soft rot has caused economic turmoil and ecological impacts leading to ginger losses and degrading effects to the fertile soil.

Yusof (1990) noted that the postharvest shelf life of ginger was cut short by sprouting, shriveling, softening and mold growth (Paull, Chen, & Goo, 1988b; Yusof, 1990). Likewise, the growth of saprophytes like *Penicillium spp.*, on cut ends and injured areas has been observed (Chen, 2014). Hence, postharvest storage methods which can help alleviating such problems are needed.

2.4 Importance of Postharvest technology:

Postharvest handling stages include harvesting, handling and storage and distribution of a commodity in respective markets (Mattos et al., 2014). While improvement in all aspects of the postharvest is necessary, storage of the commodities has important implications for reducing the food losses. Since the beginning of agriculture, man has been faced with the tricky problem of storage of the harvested crop to keep it in good condition for future uses. Most fruits and vegetable have short shelf-life and rapidly ripen at room temperature (Wang et al., 2005) hence we modify and control the atmospheric conditions in order to improve storability. The first recorded instance of the use of modified atmosphere storage in agriculture was in the Roman era (Varrò, 1800), even though it is believed that the people in the Middle east were well versed in these techniques more than several thousand years prior to the Roman era (Kays, 1991). Most storage techniques developed over the past 70 years have dealt with reduction of the storage temperature to change in the respiration rates of the stored fruit or vegetable (Chong, Peng, Yin, Lipscomb, & Chung, 2013; Farber et al., 2003) which ultimately results in increase in CO_2 and decrease in the O_2 present.

Modified atmosphere (MA) as a postharvest storage technique can be classified into two categories viz. the modified atmosphere packaging (MAP) and the controlled atmosphere storage (CAS). The key difference between these two is that in the CAS the gas level is maintained strictly whereas in the MAP, the gas mixture is purged initially and it changes later depending on respiration of the stored perishables (Majidi et al., 2014). The atmosphere in the storage vessel is modified and the gas phase composition is maintained in such a way as to retard the respiration rate. This leads to increased lifespan and regression in food deterioration (Chong et al., 2013). The shelf life of a fruit or vegetable is inversely proportional to its respiration rate, a lowered respiration rate helps to increase the shelf life (Farber et al., 2003). The MAP is applied as a packaging method or as a coating on the perishable material, mainly during the transportation and marketing of the commodity. Method of application of this passive technique depends primarily on the type of fruit or vegetable to be stored due to the variation in respiration rate among fruits and vegetables and the gas diffusion in the packaging relies on temperature and oxygen concentration in the packaging. Polymer modification and bio-nanocomposite packaging are in development to improve the shelf life of materials under MAP (Figoli et al., 2007). Knowledge of gas diffusion and respiration rate of perishables are required to predict the interactions between the polymer packing and the external atmosphere, the internal atmosphere, and the stored commodity.

Major applications of MAP are in storage and packing of smaller quantities whereas CA finds application for larger quantities of perishables. The definition of controlled atmosphere storage infers the addition and/or removal of gases from the chamber in which the perishables are stored (Plasse, 1986). The first controlled atmosphere storage was constructed and used for apple storage in 1929 and was mainly based on the principle of elevated CO_2 and reduced O_2 for increasing the shelf life of the commodity stored (Beaudry, 1999).

2.5 Controlled atmosphere storage:

CA storage essentially involves maintaining the gas composition, via addition or by removal of gases (mainly N_2 and CO_2) by flushing the chamber and then using pressurised cylinder(s) of the gases to regulate the desired concentration of the gases inside the storage chamber (Navarro, 2012). The CAS relies on the adequately controlled temperature, relative humidity, and atmospheric gas composition which are in turn affect the plant metabolism (Gariépy et al., 1986).

Gas separation is necessary to maintain a definite concentration of gases within the storage chamber. Hence, the polymeric membranes used as windows at the interface of the sink and sources of the gas are an essential component of the CAS system. These membranes are involved in the transport of gases between the chamber and the gas from the cylinders. Thompson (1971) had observed that, dropping the temperature is restricted by the perishables' predisposition to premature ripening and chilling injuries, and it damage the plant tissue during storage (Thompson, 1971). This basic understanding of modified/controlled atmosphere storage systems, will help to develop and implement in postharvest storage.

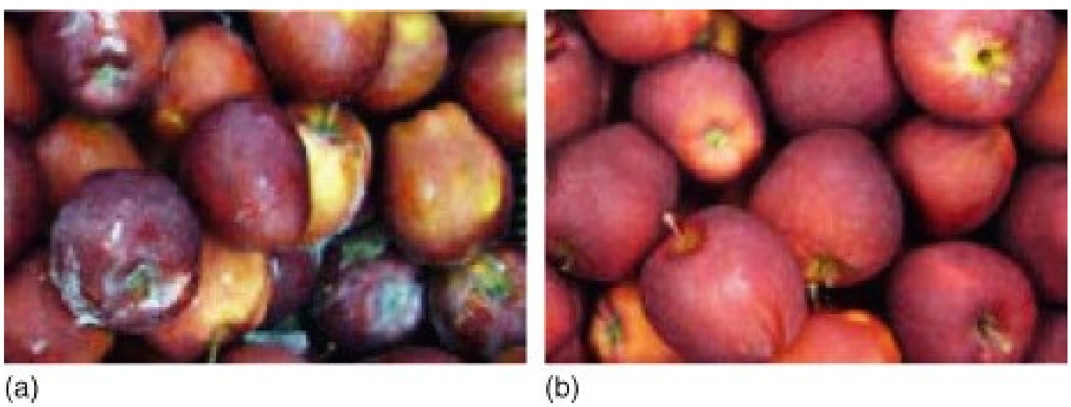

Fig. 5: Effect of controlled atmosphere (CA) on apple decay. (a) Refrigerated storage; (b) CA + refrigerated storage (Bodbodak & Moshfeghifar, 2016)*

* Reprinted from Eco-Friendly Technology for Postharvest Produce Quality, *1st Edition*, Bodbodak et al., Advances in controlled atmosphere storage of fruits and vegetables, 39-76, (2016), with permission from Elsevier

CO_2 is the most important gas in CAS, since it not only reduces the microbial activity but also inhibits the activity of certain enzymes that are leading to the production of ethylene gas, which is responsible for fruit/vegetable ripening. Also, the increased level of CO_2 further slows down the metabolism of the stored food commodity. If lower concentrations of oxygen are available in the storage chamber, the reactions taking place at the surface of the commodity will be slow. This leads to decelerated ripening and senescence of the fruit and vegetable. Hence a higher CO_2 concentration and a lower O_2 concentration is key in the development of an optimum CA storage system. Along with maintaining the relative humidity, the temperature needs to be lower than room temperature (depending on the stored commodity) to alleviate the effects of bruising or other such surface injuries and to avoid discoloration of the commodity. Fig. 5 shows the effect of CAS on apple decay with only refrigerated storage and with a combination of refrigerated storage and CAS.

Table 3: Differences between CAS and MAP

CONTROLLED ATMOSPHERE STORAGE	MODIFIED ATMOSPHERE PACKAGING
Active storage which inhibits ripening and ageing processes by slowing respiration, hence maintaining flavour and quality.	Passive storage that helps extend marketing period by maintaining the quality of fresh products, reducing food waste in the cold chain.
Commonly used for agricultural storage of dry commodities (grains, legumes, oilseed) and fresh produce (fruits or vegetables).	Packaging commonly used for food (fruits, vegetables, meat and meat products, seafood), and drugs.
Atmospheric gases, RH and temperature are modified.	Atmospheric gases surrounding food in packaging are modified.
The concentration of gases is maintained at desired levels.	Gas composition changes over time due to respiration.
Larger areas of storage (vats/rooms/silos)	Small packing units (active packaging/ biopolymer films)
Long term storage (2 to 4 times more than usual)	Comparatively short term storage
Used for: apples, pears, celery, carrots, bananas, grains, olives, coffee etc.	Used for: meat, fresh-cut vegetables or fruits, cheese, baked foods, seafood etc.

2.6 External factors affecting the perishable food in storage:

The temperature of storage environment is one of the mostly understood factors affecting the perishables. When the fruits and vegetables are stored at temperatures in the range of 0 to 14 °C, the biological, biochemical, and physiological activities in them are retarded at it lead to slowing down the senescence viz. slow ripening with added benefit of lesser growth of pathogenic organisms from the environment. The surrounding levels of relative humidity affects the loss of moisture from the stored perishables and it was observed that higher the relative humidity better the storage condition. The third factor influencing the storage of perishable foods is gas concentrations in the storage chamber, as explained in the section above, lower oxygen and higher carbon dioxide concentrations help in prolonging the shelf-life of the perishable food materials.

2.7 Understanding the respiration and role of atmospheric gases in it:

Respiration is a major reaction to be controlled in long term storage of fruits and vegetables. It is the oxidative breakdown of complex substrates naturally occurring in plant cells, to by-products including CO_2, and H_2O. Energy (ATP) and other by-products produced in this reaction are used in other metabolic processes, to maintain the health of the product (Saltveit, 2004). Commodities with higher respiration rate tend to have shorter storage life and vice versa. By controlling the respiration rate, it is possible to control to an extent the senescence and ripening of fruits and vegetables (Wills, Lee, Graham, McGlasson, & Hall, 1981).

Metabolic pathways in fruits and vegetables are very closely linked to the respiration process, hence the respiration can be used as a benchmark to study the physiological and metabolic state of the plant tissues (Saltveit, 2004). Assuming glucose as the substrate and aerobic respiration is taking place, the overall respiration reaction can be represented as:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 38ATP \quad (1)$$

Three complex paths catalyzed by specific enzymes play the following roles in plant metabolism: addition of phosphate group to substrate (glucose) molecule, modulate the substrate molecule and break it down to a simple molecule. The three important pathways that complete these functions are glycolysis, tricarboxylic acid (TCA) cycle and electron transport chain (Fonseca, Oliveira, & Brecht, 2002).

Glycolysis, as its appellation suggests, is essentially the breakdown (lysis) of glucose that takes place in the cell cytoplasm. Each glucose molecule produces two pyruvate molecules. Ten separate reactions are catalyzed by their distinct biocatalysts. Most important of which are phosphofructokinase (PFK) and pyruvate kinase (PK) enzymes. The energy production can be altered by controlling the enzymatic activity of PFK and PK involved in glycolysis. The ATP is used as a negative feedback inhibitor to control the activity of PFK. Glycolysis produces 2 ATP and 2 NADH molecules from lysis of each molecule of glucose (Saltveit, 2004).

The Tricarboxylic acid (TCA) cycle, generally known as the Kreb's cycle involves the breakdown of pyruvate molecule, produced through the glycolysis, to carbon dioxide and takes place in the mitochondria. It includes nine sequential enzyme-catalyzed steps in which pyruvate is decarboxylated to produce acetate which undergoes enzymatic reactions to form acetyl-CoA. This further leads to the production of citric acid (tricarboxylic acid). Through a series of seven consecutive reactions involving rearrangement, oxidations, and decarboxylation; the citric acid is converted back to oxaloacetate which will react with another acetyl-CoA molecule for the cyclic reactions to continue.

Electron transport chain taking place in the membranes of the mitochondria consists of ATP production from intermediates obtained from the TCA cycle. The intermediate compounds include high energy molecules like $FADH_2$ and NADH. One NADH molecule yields three ATP molecules, while one $FADH_2$ molecule yields two ATP molecules. ATP production is dependent on the chemical environment (pH and ion concentrations) within the cell and the mitochondria.

2.8 Role and relevance of atmospheric gases in the modified atmosphere storage

Atmospheric change in CO_2 concentrations has been demonstrated to cause a change in the physiological behavior and growth of plants (Mattos et al., 2014). In the MAP, higher CO_2 concentration and lower O_2 concentration are maintained. The connections between the O_2 and CO_2 concentrations inside the MAP are simple to understand, by developing an environment rich in CO_2 and depleted O_2, the aerobic respiration can be inhibited and prevents the loss of moisture (Raghavan, 1996).

By using membrane technology, the rate of gas diffusion can be maintained and controlled easily. While refrigeration has its advantages, there are disadvantages like tissue damage and loss in the taste of stored fruits or vegetables. Ethylene helps in the ripening of fruit by chemical processes which are not thoroughly understood yet (Wills et al., 2001).

Respiration rate defines the amount of oxygen consumed by plant material; it is expressed as;

$$r_{o2} = W \cdot f(T, p_{O2}, p_{CO2}) \tag{2}$$

Where W= mass of the produce, T = temperature, p_{O2} and p_{CO2}= partial pressures of oxygen and carbon dioxide in the immediate atmosphere, and f (T, p_{O2}, pC_{O2}) gives O_2 used up per unit mass (Kirkland, Clarke, & Paul, 2008).

Another important term is the respiratory quotient (RQ), defined as the ratio of carbon dioxide produced to oxygen consumed. Simply put,

$$RQ = \frac{r_{co2}}{r_{o2}} \tag{3}$$

Table 4: Respiration rates of some food commodities adapted from USDA handbook 66 (Saltveit, 2004)

CLASS	RANGE AT 5^0C mg CO_2 kg $^{-1}$ H^{-1}	COMMODITIES
Very low	<5	dates and nuts
Low	5 to 10	apple, citrus, grape, kiwifruit, onion, potato
Moderate	10 to 20	apricot, banana, cherry, peach, pear, plum, fig, cabbage, carrot, lettuce, pepper
High	20 to 40	strawberry, blackberry, raspberry, cauliflower, lima bean, avocado
Very High	40 to 60	artichoke, snap bean, brussel sprouts, cut flowers
Extremely High	>60	asparagus, broccoli, mushroom, pea, spinach, sweet corn

2.9 Gas control systems used in producing and maintaining controlled atmosphere:

Selection of gas control system depends on the sensitivity of stored produce to atmospheric gases. Hence, understanding of the concept of controlled atmosphere, and the gases which affect during storage of fruits and vegetables are important. The range of regulating methods and equipment depend on various factors like airtightness of the storage chamber, monitoring of the gas concentrations maintained inside the chamber, the stored product characteristics, and the economic feasibility of the storage regimen. The selection of storage appropriate for a particular food commodity is important.

The types of equipment for the control of gas concentration are classified based on the gas whose concentration is modified to produce the storage conditions required for the selected food material.

2.9.1 CO_2 control system:

CO_2 scrubber systems are commonly used in the developing countries for control of CO_2 levels because it involves the use of a cheaper equipment with a readily available material for assembly of the system. When CO_2 scrubbers were first developed, alkalis like caustic soda (NaOH), potash (KOH), dry lime ($Ca(OH)_2$) were used for converting CO_2 to carbonates. When a solution of NaOH is passed through tubes, it leads to the absorption of CO_2 from the system, leading to a reduction in CO_2 levels (Raghavan, 2005). A similar procedure applies with the use of potash, where the reaction leads to the formation of Na_2CO_3 and K_2CO_3 which are contaminants causing corrosion and requires cautious handling and disposal methods (Bodbodak et al., 2016). Due to these disadvantages, the methods involving the use of corrosive caustic chemicals were discontinued.

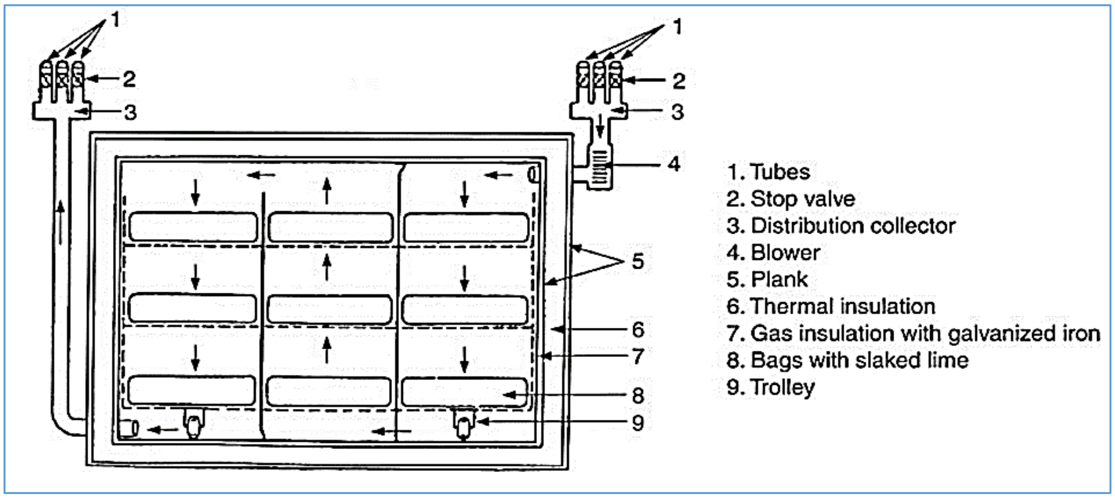

*Fig. 6: CO_2 scrubber (Gopala Rao, 2015)**

* Reprinted from Engineering for Storage of Fruits and Vegetables, 1st Edition, Chandra Rao, Chapter 32 – Gas Generators for Controlled Atmosphere Storage, 2015, with permission from Elsevier.

However, calcium hydroxide or hydrated lime scrubbers are easy to build but require a lot of slaked lime to produce the desired effect. The absorption of CO_2 using $Ca(OH)_2$ is commonly represented as the reaction in Equation (4):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

The absorbent viz. hydrated lime is completely replaced when saturated with CO_2. Approximately 6-10 kg of slaked lime is required per ton of produce, depends on the type of stored fruit or vegetable (Fig. 6). Construction of such equipment is easy, a sealed plywood box is loaded with half of the required amount of hydrated lime required for total storage time and is connected to the storage room. The air flow is controlled by using fans or passively using mechanical constructions. As the CO_2 reacts with the calcium hydroxide, the rate of this reaction decreases. To monitor to find the process completion, an approximate increase in mass of lime from 22 kg to 30 kg, is used as a guideline (Rao, 2015). Water-based CO_2 scrubbers are preferred due to high CO_2 absorption rate compared to other methods. Absorption can further be increased by the use of brine solution which passes through the storage area absorbing CO_2, thus maintaining the required CA.

Newer methods involve the use of activated carbon and use of sodium or aluminium silicate molecular sieves (Bodbodak et al., 2016; Rao, 2015). Cylindrical tubes are packed with these components and the air is passed through it, leading to the removal of carbon dioxide gas. Though the re-generation of these materials is required, it can easily be achieved using simple procedures.

2.9.2 Oxygen control systems:

Reducing the level of oxygen is a straightforward process, plant respiration and combustion are two processes which lead to a quick and smooth decrease in O_2 levels. Flushing with nitrogen gas is used to reduce oxygen levels. It helps to slow down respiration; but care should be taken to avoid structural damage to the stored produce (Bodbodak et al., 2016).

Until 1990, an open flame with propane as the fuel was used to control O_2 levels, but these systems weren't environment-friendly, and an additional system for CO_2 removal was required (Rao, 2015). In contrast to the flame-assisted system, the catalytic combustion systems yield lesser toxins and leads to an efficient process to control O_2 levels. It involves the cracking of ammonia at high temperature to N_2 and H_2 ($2NH_3 \rightarrow N_2 + 3H_2$); and the H_2 is then converted to water by consuming oxygen in the unit ($2N_2 + 6H_2 + 3O_2 \rightarrow 6H_2O + 2\ N_2$).

2.9.3 Ethylene control systems:

Oxidation of ethylene leads to the formation of carbon dioxide and water, which can be removed using a CO_2 scrubber immobilized with a catalyst. A carbon-heat hybrid scrubber showed reduced levels of ethylene when used in storage of tomatoes (Martínez-Romero et al., 2009). Potassium permanganate ($KMnO_4$) adsorbs on aluminium silicate bead scrubbers leading to concurrent ethylene absorption. This process is easily detected due to color change of $KMnO_4$ from purple to brown that can be observed.

2.9.4 Gas separator systems:

- Pressure swing adsorption (PSA) systems: The system has a molecular sieve selective to O_2 gas is the core component of the system. A filtered and compressed stream of air passes through the system as an input, while the output mainly consists of nitrogen gas (90-99 %). The absorbed O_2 gas is then released from the sieve by depressurising the unit, as the name pressure swing adsorption suggests (Fig. 7) (Raghavan, 1996).

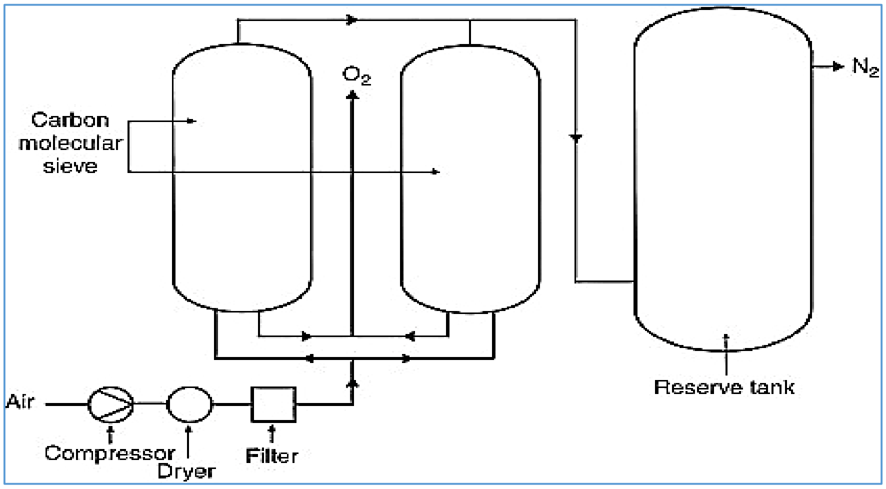

*Fig. 7: Pressure swing adsorber (PSA) for nitrogen (Bodbodak & Moshfeghifar, 2016)**

- Hollow Fiber membrane (HFM) systems: In this system, hollow fibers constructed using semi-permeable membranes are used, and heated compressed air is forced through them (Fig. 8). Since the membranes are more permeable to CO_2 and O_2, it leads to removal of these gases and nitrogen gas continues to remain in the CA room (Rao, 2015; Raghavan, 1996).

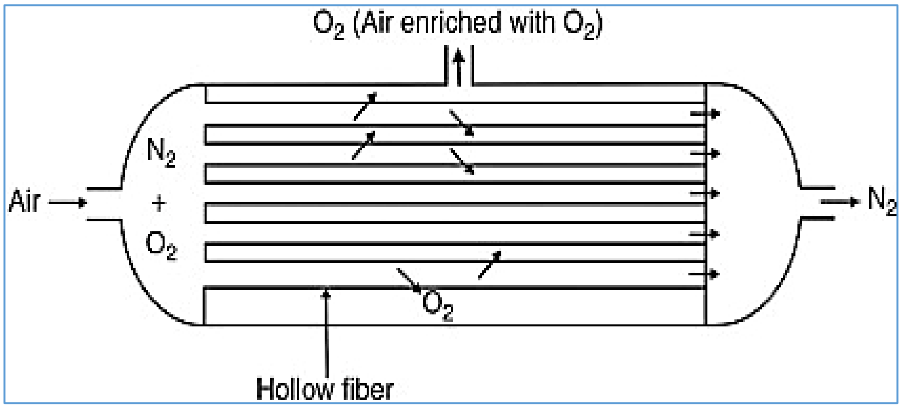

*Fig. 8: Hollow fiber membrane (HFM) for N_2 (Bodbodak & Moshfeghifar, 2016)**

* Reprinted from Eco-Friendly Technology for Postharvest Produce Quality, *1st Edition*, Bodbodak et al., Advances in controlled atmosphere storage of fruits and vegetables, 39-76, (2016), with permission from Elsevier

2.10 MA systems

2.10.1 Pallet system

Pallet packing systems with silicone membrane were used to produce the first commercial controlled atmosphere system (Raghavan et al., 1984). In this system, a pallet box wrapped in heavy gauge polythene is used, with a window fitted with silicone-based membrane acts as the gas exchange regulator and a calibrated hole is used for pressure regulation. Being more or less compact, this system has various advantages including the ease of manipulation, marketability of a fraction of the whole produce stored without affecting the CA in the other pallet boxes (Rao, 2015). Also, these systems don't need modifications which are ordinarily required for controlled atmosphere storage. Nonetheless, some additional space is required for in the storage system for satisfactory ventilation, and the boxes need to be individually wrapped and unwrapped while storing and extra care needs to be given to avoid any physical damage to the system and the food material stored in it.

2.10.2 Silicone membrane system

In the late 1960s, the French scientist Marcellin acknowledged the potential of membrane technology in fruit and vegetable storage. By creating an atmosphere abundant in CO_2 and limited

O_2, moisture loss could be prevented and suppression of aerobic respiration could be achieved (Barrett et al., 2004). The principal on which silicone membrane systems are based is that the silicone membranes have different permeability to different gases, hence diffusion across membrane takes place at different rates based on the physical and chemical properties of the gases (Gariépy et al., 1986). Product respiration and diffusion across the membrane result in the desired atmosphere for the perishables inside the storage container.

To calculate the area of membrane across which the gas exchange takes place, Equations (5-6) can be used based on the concentration of CO_2 and O_2, respectively.

Area of membrane based on CO_2 concentrations,

$$A = \frac{RR_{CO_2} \cdot m}{K_{CO_2} \cdot pp_{CO_2}} \tag{5}$$

Area of membrane based on O_2 concentrations,

$$A = \frac{RR_{O_2} \cdot m}{K_{O_2} \cdot pp_{O_2}} \tag{6}$$

Where, A = membrane area of silicone membrane (m^2)

RR_{CO2} = respiration rate based on CO_2 (l/kg day)

RR_{O2} = respiration rate based on O_2 (l/kg · day)

m = mass of product stored (kg)

K_{CO2} = permeability of membrane to CO_2 (m^3/ day · m^2 · atm)

K_{O2} = permeability of membrane to O_2 (m^3/ day · m^2 · atm)

pp_{CO2} = partial pressure across membrane for CO_2 (atm)

pp_{O2} = partial pressure across membrane for O_2 (atm)

The chamber should be hermetically sealed i.e. air-tightness should be maintained for such system.

2.10.3 Atmolysair system

Atmolysair systems are a modification of Marcellin system and were developed in Canada (Gariepy et al., 1989). The system consists of gas diffusion panels placed in parallel alignment in a hermetically sealed container with two separate gas flow paths and a control panel (Fig. 10). Air flow in the unit is maintained using two timed-blowers. Gas analysis is performed at regular intervals to check whether any modification in the blower speeds is necessary.

The Marcellin systems use rectangular silicone bags instead of diffusion panels and used for larger storage rooms (Fig. 9). The Atmolysair systems offer better gas exchange since both the streams can be controlled, they are easy to operate and can be modified to be automated. Hence, they have an upper hand over the Marcellin systems (Raghavan, 1996).

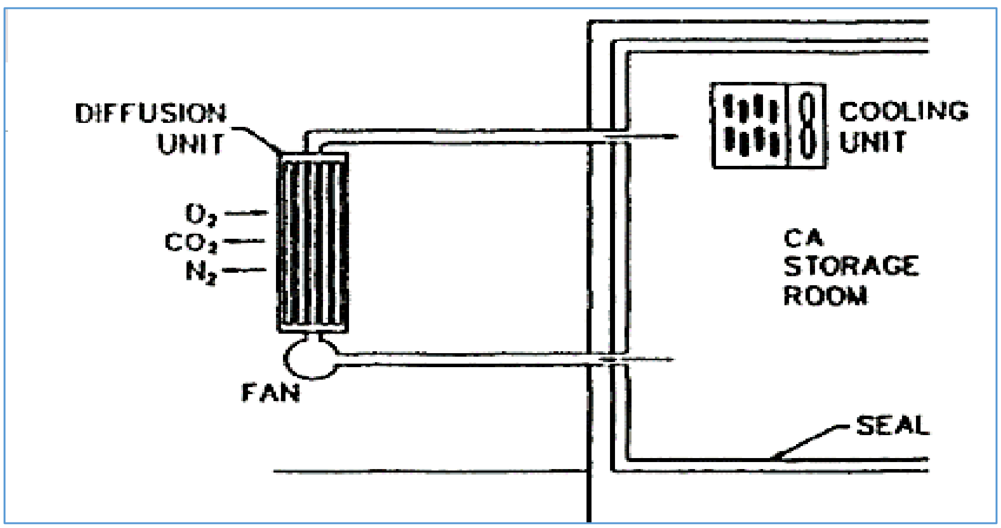

Fig. 9: Marcellin system (Raghavan, Vigneault, & Gariépy,1996)*

* Reprinted from Processing fruits : science and technology, Edition 1, Somogyi et al., Refrigerated and controlled atmosphere storage, 1996, with permission from Technomic Pubg. Co. Inc.; conveyed through Copyright Clearance Center, Inc.

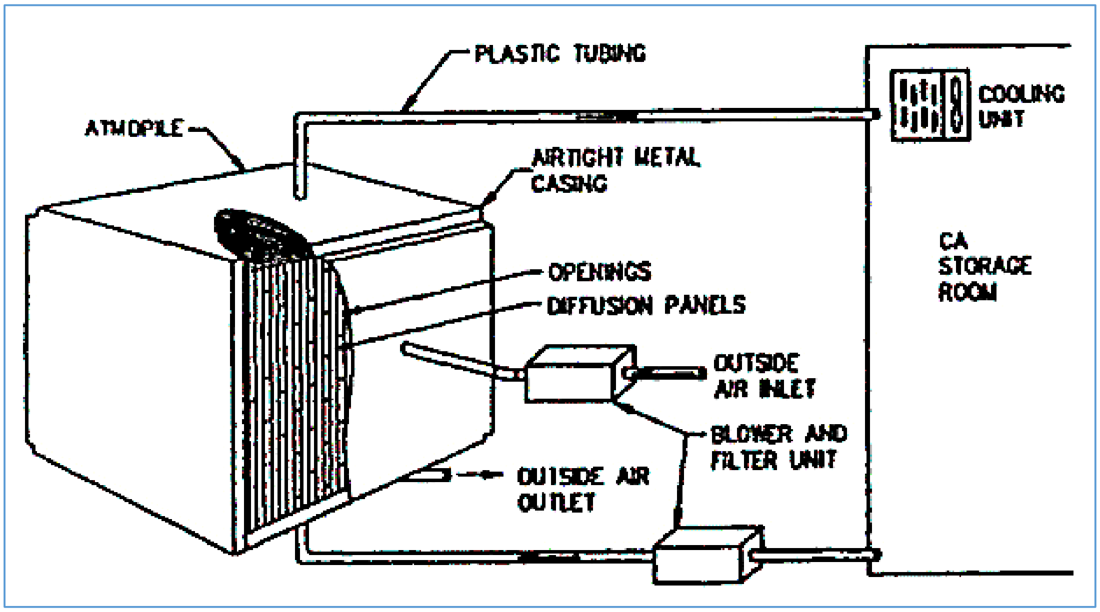

Fig. 10: Atmolysair system (Raghavan, Vigneault, & Gariépy,1996)*

* Reprinted from Processing fruits : science and technology, Edition 1, Somogyi et al., Refrigerated and controlled atmosphere storage, 1996, with permission from Technomic Pubg. Co. Inc.; conveyed through Copyright Clearance Center, Inc.

2.12 Other commercially available systems

Table 5: Examples of commercial storage systems adapted from FDA (2001)

Commercial storage systems	Properties	Usage
Tom-Ah-Toes (Natural Pak Produce, USA)	Long, narrow box over-wrapped with the gas permeable film. Activated lime and $CaCl_2$ sachet to absorb CO_2	Tomatoes, avocados, mangoes
FreshSpan ™ (SunBlush Technologies Inc., Canada)	Corrugated paperboard FreshSpan™ box lined with breathable plastic membrane, made airtightly	Fresh-cut asparagus, broccoli, cauliflower, avocados, berries
FreshHold (Hercules Chemical Co., USA)	Calcium carbonate embedded in polypropylene labels	Broccoli, asparagus, cauliflower and cherries
P-Plus films (Courtaulds Packaging, USA)	Spark perforated films with non-uniform perforation used to enable gas exchange	Brussels sprouts, lettuce, broccoli, fresh mushrooms, and bean sprouts
MaptekFresh™ (SunBlush Technologies Inc., Canada)	Biotech based MAP helps preserve cut vegetables and circumvents ethylene's effects	Fresh-cut pineapple, fruit salad, cut tomatoes
MAPAX ® (AGA, Sweden)	Each product is tested to determine optimal atmospheric conditions, selecting exact gas mixture and the best film for product bearing in mind respiration rate, temperature, film type, packing volume	Fresh-cut produce, mushrooms, pre-peeled potatoes, lettuce
Tectrol System (TransFRESH Co., USA)	Palletized bulk unit packed with a barrier plastic film; gases are injected and pallet, sealed	Strawberries (short term transport)
Laminated boxes (Georgia Pacific, Weyerhaeuser and Tamfresh Ltd.)	Laminated cartons on the outside or inside of the cardboard liner. Reduction in moisture loss and helps air flow	Strawberries, broccoli

Film Convertors	Based on requirements, the converters (companies) buy resin or film and modify it suitably. They are more flexible with respect to specific applications of the requested film	Variable/product specific

2.13 Automated controlled atmosphere systems

With developments in computer technology, automation of controlled atmosphere storage seems like a very straightforward approach. To ensure the optimum quality and efficiency, automation not only provides various advantages but it is also essential nowadays. Due to the dynamic behavior of CA systems, an exhaustive study of symbiotic nature of CA systems is needed (Gariepy et al., 1987). Gas balance can be affected by level of the hermetic sealing of chamber and its integrity, the physiological response of the stored produce, equipment regulating CO_2 and O_2 and changes that occur in the weather (Rao, 2015).

The general approach to automation is to stabilise and maintain the CO_2 and O_2 levels in the chamber while balancing the temperature and humidity. The control system is expected to reduce the differences in the process variables and the set points. The proficiency of computerised systems would be effectively deciding the type and magnitude of interventions required for operating the gas regulating unit.

Commercial PC-based systems are available now for supervising and controlling CA systems. The CAS equipment is built using a microprocessor unit, a gas analyser (for CO_2/O_2 measurement), and temperature and humidity sensors along with a gas regulating device. Such equipment should have a back-up in the case of power or equipment failure. There is a need for manual labour for monitoring of the CA conditions. The storage operator can enter required parameters and monitor the storage process via the PC output.

References

Abd Allah, E. S. H., Makboul, R., & Mohamed, A. O. (2016). Role of serotonin and nuclear factor-kappa B in the ameliorative effect of ginger on acetic acid-induced colitis. *Pathophysiology, 23*(1), 35-42. doi:10.1016/j.pathophys.2015.12.001

Afek, U., & Kays, S. J. (2004). Postharvest physiology and storage of widely used root and tuber crops. *Hort Rev, 30*, 253-318.

Akamine, E. K. (1977). Tropical and subtropical crops in Hawaii. *CSIRO Food Research Quarterly, 37*(1), 13-20.

Ali, B. H., Blunden, G., Tanira, M. O., et al. (2008). Some phytochemical, pharmacological and toxicological properties of ginger (Zingiber officinale Roscoe): a review of recent research. *Food Chem Toxicol, 46*(2), 409-420. doi:10.1016/j.fct.2007.09.085

An, K., Zhao, D., Wang, Z., et al. (2016). Comparison of different drying methods on Chinese ginger (Zingiber officinale Roscoe): Changes in volatiles, chemical profile, antioxidant properties, and microstructure. *Food Chemistry, 197, Part B*, 1292-1300. doi:10.1016/j.foodchem.2015.11.033

Baliga, M. S., Haniadka, R., Pereira, et al. (2011). Update on the Chemopreventive Effects of Ginger and its Phytochemicals. *Critical Reviews in Food Science and Nutrition, 51*(6), 499-523. doi:10.1080/10408391003698669

Barrett, D. M., Somogyi, L., & Ramaswamy, H. S. (2004). *Processing Fruits: Science and Technology, Second Edition*: CRC Press.

Beaudry, R. M. (1999). Effect of O2 and CO2 partial pressure on selected phenomena affecting fruit and vegetable quality. *Postharvest Biology and Technology, 15*(3), 293-303. doi:10.1016/S0925-5214(98)00092-1

Bodbodak, S., & Moshfeghifar, M. (2016). 2 - Advances in controlled atmosphere storage of fruits and vegetables A2 - Siddiqui, Mohammed Wasim *Eco-Friendly Technology for Postharvest Produce Quality* (pp. 39-76): Academic Press.

Britannica, E. (2016). ginger.

Butler, E. J. (1907). An account of the genus Pythium and some Chytridiaceae: Thacker.

Paull R. E. & Chen, C. C.(2014). *Ginger* USDA (Ed.) *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*

Chong, K. L., Peng, N., Yin, H., et al. (2013). Food sustainability by designing and modelling a membrane controlled atmosphere storage system. *Journal of Food Engineering, 114*(3), 361-374. doi:10.1016/j.jfoodeng.2012.08.027

Chung, H.-S., & Moon, K.-D. (2011). Sprouting and quality control of fresh ginger rhizomes by modified atmosphere packaging with film perforation. *Food Science and Biotechnology, 20*(3), 621-627. doi:10.1007/s10068-011-0088-4

Directorate of Marketing and Inspection (AGMARK) (2005). Spice Grading and Marking Rules, India.

FAO, (2013). The State of Food Insecurity in the World 2013. Multiple Dimensions of Food Security. http://www.fao.org/docrep/018/i3434e/i3434e00.htm [last accessed on 13 July 2016].

Farber, J. N., Harris, L. J., Parish, M. E., et al. (2003). Microbiological Safety of Controlled and Modified Atmosphere Packaging of Fresh and Fresh-Cut Produce. *Comprehensive Reviews in Food Science and Food Safety, 2*, 142-160. doi:10.1111/j.1541-4337.2003.tb00032

Figoli, A., De Luca, G., & Drioli, E. (2007). Polymeric capsule production for food packaging application. *Italian journal of food science, 19*, 90-96.

Fonseca, S. C., Oliveira, F. A. R., & Brecht, J. K. (2002). Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: a review. *Journal of Food Engineering, 52*(2), 99-119. doi:10.1016/S0260-8774(01)00106-6

Food, & Agriculture Organization of the United, N. (2014). FAOSTAT.

Forero, M. P. (2007). Storage life enhancement of avocado fruits. (Master's dissertation), McGill University.

Funk, J. L., Frye, J. B., Oyarzo, et al. (2016) Anti-Inflammatory Effects of the Essential Oils of Ginger (Zingiber officinale Roscoe) in Experimental Rheumatoid Arthritis. *PharmaNutrition*. doi:10.1016/j.phanu.2016.02.004

Gariepy, Y., & Raghavan, G. S. V. (1989). A mathematical model for a pressure regulated silicone membrane gas permeator for CA storage *Paper - American Society of Agricultural Engineers; 1989. (89-4049):16 pp. 16*

Gariépy, Y., Raghavan, G. S. V., & Thériault, R. (1986). Controlled atmosphere storage of celery with the silicone membrane system. *International Journal of Refrigeration, 9*(4), 234-239. doi:10.1016/0140-7007(86)90096-4

Gopala Rao, C. (2015). Chapter 33 - Equipment for Producing and Regulating Controlled Atmosphere. In C. G. Rao (Ed.), *Engineering for Storage of Fruits and Vegetables* (pp. 583-598): Academic Press.

Govindarajan, V. S. (1982). Ginger--chemistry, technology, and quality evaluation: part 1. *Critical Reviews in Food Science and Nutrition, 17*(1), 1-96. doi:10.1080/10408398209527343

Gross, K. C., Wang, C. Y. & Salveit, M. (2014). The commercial storage of fruits, vegetables, and florist and nursery stocks. United, States Agricultural Research, Service.

Gümüşay, Ö. A., Borazan, A. A., Ercal, N., & Demirkol, O. (2015). Drying effects on the antioxidant properties of tomatoes and ginger. *Food Chemistry, 173*, 156-162. doi:10.1016/j.foodchem.2014.09.162

Hubert, B., Rosegrant, M., van Boekel, et al. (2010). The Future of Food: Scenarios for 2050. *Crop Science, 50*(Supplement_1), S-33-S-50. doi:10.2135/cropsci2009.09.0530

Jakribettu, R. P., Boloor, R., Bhat, et al. (2016). Chapter 50 - Ginger (Zingiber officinale Rosc.) Oils A2 - Preedy, Victor R *Essential Oils in Food Preservation, Flavor and Safety* (pp. 447-454). San Diego: Academic Press.

Kader, A. A. (2004). *Increasing food availability by reducing postharvest losses of fresh produce.* Paper presented at the V International Postharvest Symposium 682.

Kader, A. A., Zagory, D., & Kerbel, E. L. (1989). Modified atmosphere packaging of fruits and vegetables. *Crit Rev Food Sci Nutr, 28*(1), 1-30. doi:10.1080/10408398909527506

Kaur, K., Saxena, A., Haniadka, R., et al. (2015). Chapter 6 - Medicinal Benefits of Ginger in Various Gastrointestinal Ailments: Use in Geriatric Conditions A2 - Watson, Ronald Ross *Foods and Dietary Supplements in the Prevention and Treatment of Disease in Older Adults* (pp. 51-61). San Diego: Academic Press.

Kawamoto, Y., Ueno, Y., Nakahashi, E., et al. (2016). Prevention of allergic rhinitis by ginger and the molecular basis of immunosuppression by 6-gingerol through T cell inactivation. *The Journal of Nutritional Biochemistry, 27*, 112-122. doi:10.1016/j.jnutbio.2015.08.025

Kays, S. J. (1991). *Postharvest physiology and handling of perishable plant products*: Van Nostrand Reinhold Inc.

Kim, D.-H., & Lee, Y.-C. (2006). Changes in some quality factors of frozen ginger as affected by the freezing storage conditions. *JSFA Journal of the Science of Food and Agriculture, 86*(10), 1439-1445.

Kirkland, B. S., Clarke, R., & Paul, D. R. (2008). A versatile membrane system for bulk storage and shipping of produce in a modified atmosphere. *Journal of Membrane Science, 324*(1–2), 119-127. doi:10.1016/j.memsci.2008.07.001

Le, D. P., Smith, M., Hudler, G. W., et al. (2014). Pythium soft rot of ginger: Detection and identification of the causal pathogens, and their control. *Crop Protection, 65*, 153-167. doi: 10.1016/j.cropro.2014.07.021

Majidi, H., Minaei, S., Almassi, M., et al. (2014). Tomato quality in controlled atmosphere storage, modified atmosphere packaging and cold storage. *Journal of Food Science and Technology, 51*(9), 2155-2161. doi: 10.1007/s13197-012-0721-0

Martínez-Romero, D., Guillén, F., Castillo, S., et al. (2009). Effect of ethylene concentration on quality parameters of fresh tomatoes stored using a carbon-heat hybrid ethylene scrubber. *Postharvest Biology and Technology, 51*(2), 206-211. doi: 10.1016/j.postharvbio.2008.07.011

Mattos, L. M., Moretti, C. L., Jan, S., et al. (2014). Chapter 19 - Climate Changes and Potential Impacts on Quality of Fruit and Vegetable Crops. In P. Ahmad & S. Rasool (Eds.), *Emerging Technologies and Management of Crop Stress Tolerance* (pp. 467-486). San Diego: Academic Press.

Misawa, K., Hashizume, K., Yamamoto, M., et al. (2015). Ginger extract prevents high-fat diet-induced obesity in mice via activation of the peroxisome proliferator-activated receptor δ pathway. *The Journal of Nutritional Biochemistry, 26*(10), 1058-1067. doi: 10.1016/j.jnutbio.2015.04.014

Morris, R. F. (1978). *Postharvest food losses in developing countries: a bibliography*: National Academies.

Mukherjee, P. K., Thomas, P., & Raghu, K. (1995). Shelf-life enhancement of fresh ginger rhizomes at ambient temperatures by combination of gamma-irradiation, biocontrol and closed polyethylene bag storage. *Annals of Applied Biology, 127*(2), 375-384. doi:10.1111/j.1744-7348.1995.tb06681.x

Naik, R., Ambrose, D. C. P., Raghavan, G. S. V., et al. (2014). Enhancing shelf life of minimally processed multiplier onion using silicone membrane. *Journal of Food Science and Technology-Mysore, 51*(12), 3963-3969. doi:10.1007/s13197-012-0898-2

Nair, K. P. P. (2013). 23 - The Postharvest and Industrial Processing of Ginger *The Agronomy and Economy of Turmeric and Ginger* (pp. 433-452). Oxford: Elsevier.

Natarajan, C. P., Bai, R. P., Krishnamurthy, M. N., et al. (1972). Chemical composition of ginger varieties and dehydration studies on ginger. *Journal of Food Science and Technology, India, 9*(3), 120-124.

National Center for, C., & Alternative, M. (2008). Ginger.

Navarro, S. (2012). The use of modified and controlled atmospheres for the disinfestation of stored products. *Journal of Pest Science, 85*(3), 301-322. doi:10.1007/s10340-012-0424-3

Park, M., Bae, J., & Lee, D. S. (2008). Antibacterial activity of [10]-gingerol and [12]-gingerol isolated from ginger rhizome against periodontal bacteria. *Phytotherapy Research, 22*(11), 1446-1449. doi:10.1002/ptr.2473

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988a). COMPOSITIONAL CHANGES IN GINGER RHIZOMES DURING STORAGE. *Journal of the American Society for Horticultural Science, 113*(4), 584-588.

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988b). CONTROL OF WEIGHT-LOSS AND SPROUTING OF GINGER RHIZOME IN STORAGE. *HortScience, 23*(4), 734-736.

Pinstrup-Andersen, P. (2009). Food security: definition and measurement. *Food Security, 1*(1), 5-7. doi:10.1007/s12571-008-0002-y

Planella, I., & Myrtle Seepersad, I. P. (1990). Proceedings of a Workshop on Post Harvest Handling of Horticultural Commodities for Export: Inter-American Institute for Cooperation on Agriculture.

Plasse, R. (1986). *Vegetable storage, respiration and design criteria in a membrane storage system.* (ML34442 M.Sc.), McGill University (Canada), Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Plotto, A. (2002). Ginger Postharvest Operations. *INPhO compendium*.

Prasad, J., & Vijay, V. K. (2005). Experimental studies on drying of Zingiber officinale, Curcuma longa l. and Tinospora cordifolia in solar-biomass hybrid drier. *Renewable Energy, 30*(14), 2097-2109. doi: 10.1016/j.renene.2005.02.007

Pruthi, J. S. (1976). *Spices and condiments*.

Raghavan, G. S. V. (2005). Refrigerated and controlled/modified atmosphere storage. *Processing Fruits, Science and technology*, 23-52.

Raghavan GSV, A. P., Gariepy Y, Vigneault C. (1996). Refrigerated and controlled modified atmosphere storage. *Processing fruits: science and technology*, 135-167.

Riad, G. (2004). Atmosphere modification to control quality deterioration during storage of fresh sweetcorn cobs and fresh-cut kernels. (3146245 Ph.D.), University of Florida, Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Saltveit, M. E. (2004). Respiratory metabolism. *The commercial storage of fruits, vegetables, and florist and nursery stocks. Agriculture Handbook, 66*.

Shaista, J. K. J. J. K. (2010). Effect of different stabilizers on the antibacterial activity of "ginger garlic paste". *J.Appl. Sci. Environ. Manag., 13*, 103-109.

Śledź, M., Nowacka, M., Wiktor, A., et al. (2013). Selected chemical and physico-chemical properties of microwave-convective dried herbs. *Food and Bioproducts Processing, 91*(4), 421-428. doi: 10.1016/j.fbp.2013.02.010

Somogyi, L., Ramaswamy, H. S., & Hui, Y. H. (1996). *Processing Fruits: Science and Technology*: Taylor & Francis.

STANDARDS, B. O. I. (2008). Ginger, Whole And Ground—Specification *Spices And Condiments*. Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002: Spices And Condiments Sectional Committee, Fad 9.

Sutarno, H., Hadad, E.A., and Brink, M. (1999). *Plant resources of South-East Asia, No.13. Spices*. Leiden: Backhuys Publishers.

Thompson, A. (1971). Storage of mango fruits. *Tropical Agriculture, 48*(1), 63-&.

Touba, E. P., Zakaria, M., & Tahereh, E. (2012). Anti-fungal activity of cold and hot water extracts of spices against fungal pathogens of Roselle (Hibiscus sabdariffa) in vitro. *Microbial Pathogenesis, 52*(2), 125-129. doi: 10.1016/j.micpath.2011.11.001

Varrò, M. T. (1800). The Three Books of M. Torentina Varro Concerning Agriculture, T. Owens (trans.): The University Press, Oxford.

Vigneault, C., Canada, Agriculture, & Agri-Food, C. (1994). *Techniques for controlled atmosphere storage of fruits and vegetables*. [Ottawa]: Research Branch, Agriculture and Agri-Food Canada.

Vijendra Kumar, N., Murthy, P. S., Manjunatha, J. R., et al. (2014). Synthesis and quorum sensing inhibitory activity of key phenolic compounds of ginger and their derivatives. *Food Chemistry, 159*, 451-457. doi: 10.1016/j.foodchem.2014.03.039

Wang, Y. S., Tian, S. P., & Xu, Y. (2005). Effects of high oxygen concentration on pro- and anti-oxidant enzymes in peach fruits during postharvest periods. *Food Chemistry, 91*(1), 99-104. doi:10.1016/j.foodchem.2004.05.053

Weiss, E. A. (2002). *Spice crops*: CABI.

Wills, R. H. H., Lee, T. H., Graham, D., et al. (1981). *Postharvest. An introduction to the physiology and handling of fruit and vegetables*.

Wills R. B. H., Warton M. A., Mussa D. M. D. N., Chew L. P. (2001) Ripening of climacteric fruits initiated at low ethylene levels. *Australian Journal of Experimental Agriculture 41* , 89–92.

Wolf, B. (2016). Confectionery and Sugar-Based Foods *Reference Module in Food Science*: Elsevier.

Yusof, N. (1990). Sprout inhibition by gamma-irradiation in fresh ginger (zingiber-officinale roscoe). *Journal of Food Processing and Preservation, 14*(2), 113-122. doi:10.1111/j.1745-4549.1990.tb00833.x

CONNECTING TEXT

The following chapter describes the experimental study on five different types of silicone-based membranes. The properties of the membranes were investigated to find out their suitability for application in modified atmosphere storage of ginger. The membranes were analysed for their surface characteristics, mechanical properties, and their permeability for the oxygen and carbon dioxide gases. Based on the results of investigations, three of these membranes were selected for experimental investigation on storing ginger rhizome under modified atmosphere conditions in order to extend the shelf-life of ginger under ambient temperature conditions.

CHAPTER III

CHARACTERIZATION OF SILICONE-BASED MEMBRANE FOR MODIFIED ATMOSPHERE STORAGE APPLICATIONS

Priyanka Kamat*, Yvan Gariépy, Jiby Kurian, Vijaya Raghavan

*Correspondence author:

Priyanka Kamat, Department of Bioresource Engineering, McGill University, QC, H9X 3V9, Canada.

Phone: +1-(438)-888-1814, Email: priyanka.kamat@mail.mcgill.ca

Abstract

Post-harvest storage technologies are implemented to prevent losses of agricultural produces which leads to food wastage. Achieving food security is a major challenge addressing by many countries world-wide and organisations like the United Nations are involved in eradicating hunger and wastage of food. Membrane-based systems provide a method for the modified atmosphere storage of fresh produce including fruits and vegetables. Silicone-based membranes exhibit different selective permeability to different atmospheric gases. This study includes the characterisation of five silicone-based membranes for surface and mechanical properties, the permeability to gases, and selectivity ratios for CO2 which are the key parameters in membrane selection for storage of fruits and vegetables.

Keywords: membrane systems, silicone, permeability, postharvest storage, Marcellin

3.1 Introduction

Postharvest handling stages include the harvesting, handling and storage and distribution of a commodity in respective markets (Mattos et al., 2014). While improvement in all aspects of postharvest is necessary, storage of the commodities has important implications for reducing the losses. Since the beginning of agriculture, man has been faced with the tricky problem of storage to make sure the harvested crop lasts longer. Most fruits and vegetable have short shelf-life and rapidly ripen at room temperature (Wang et al., 2005) hence we modify and control the atmospheric conditions in order to improve storability. The modified atmosphere storage is classified either as controlled atmosphere storage (CAS) or modified atmosphere packaging (MAP). The principal difference between these two systems is the control of the atmosphere around the stored produce, in the CAS the atmosphere is constantly monitored and modified to maintain at pre-determined conditions.

Modified atmosphere involves active alteration of gas composition within the container or package (Finnegan et al., 2013). By natural flux of gases, the system is able to maintain lower respiration rate, tolerable ethylene content,and conditions for reducing aging process (Fonseca et al., 2002). The design of MA systems should be done carefully; modelling the respiration rate helps to understand when a steady state gas concentration is achieved and and also helps in developing a system which is actually effective for the storage of fresh produce. Fonseca et al. (2002) have listed the parameters that are needed to be taken into consideration before finalising the design and construction of a MA system. Factors like the product characteristics, the ratio of mass stored to the storage volume, the recommended atmospheric conditions, permeability of membrane used in packaging and the effect of change in temperature and pressure on the permeability of the membrane, and the effect of change in temperature and gas composition on the respiration rate of the produce are needed to be taken into consideration (Fonseca et al., 2002).

The atmosphere of storage is comprised of the various gases including CO_2, O_2, C_2H_4, that are connected to the plant's respiration and metabolic activities, and the gases initally present in the storage chamber. The factors that are affecting the storage of fruits and vegetables are the temperature of storage, pressure, relative humidity, and the concentration of atmospheric gases. Permeabilities generally tend to increase with a rise in temperature or pressure of the ambient air

(Donohue et al., 1989). Other factors include the type of fruit/vegetable stored, the species/cultivar of the stored produce, respiration rate, the age of stored produce, etc.

For modified atmosphere packaging materials, we realise the need for better degradability and recyclability. Glass and metal packaging help avoid unnecessary mass transport as barriers; plastic materials are favoured for their versatile characteristics, such as light weight, and cost effectiveness. The fact, that 40% of the use of plastics is for the packaging of materials, with half of it is for packaging of food, is giving us an idea of the vastness, and the scale of application of plastics in food packaging (Rhim et al., 2013).

The focus of many research studies has been in the development of composites based on bio-polymers, and it is worth noting its importance in food distribution. Such polymeric composites, generally have enhanced properties due to their unique compositions. While being biodegradable, they also possess features like antibacterial properties, pH indication, lower water vapor permeability, and can also be used as carriers of enzymes (Rhim, 2007; Shchipunov, 2012). Such composites have been explored for applications in the textile, cosmetic, pharmaceutical, food as well as the medical industries. Though these composites cannot be used on a large scale yet, they are suitable for various small compact packaging applications.

For large-scale storage of fresh produce, silos or large storage rooms are used. Various systems are implemented for such large-scale storage systems including the pallet system, Marcellin system (Kok et al., 1982), Atmolysair system (Somogyi et al., 1996), diffusion system (Stewart et al., 2005), and the membrane-based system (Raghavan et al., 1982). The membrane-based system makes use of a polymeric or elastomeric material that acts as a gas exchange barrier to producing a modified atmosphere. Different types of membranes are available with different permeabilities to particular gases and water vapour, sealing effects, and physical properties. Selection of film/membrane depends on the commodity to be stored and the required atmospheric composition for storage. Silicone-based membrane control systems utilise the silicone membrane which is selectively permeable to certain gases and thus helps in maintaining the controlled atmosphere inside the storage container.

Silicone membrane based storage system can be applied to various fruits and vegetables. Silicone is selectively permeable viz. it is highly permeable to ethylene while it has low permeability to water vapour, which are important advantages over other modified atmosphere storage systems (Forero et al., 2007). Based on physical and chemical properties, the diffusion of different gases occurs at different rates. The final required gas concentration in such systems is achieved through two ways: (1) by the respiration of stored product; and (2) by the diffusion of gases across the silicone membrane (Gariépy et al., 1986); with an increase in the CO_2 levels and a decrease in O_2 levels.

Silicone membrane are selectively permeable and have different gas permeability for different atmospheric gases. Permeation of materials across a membrane takes place in three steps:

(i) The absorption of the permeating molecule on the membrane surface (condensation);
(ii) Solution of the permeating molecule into the membrane (mixing);
(iii) Active diffusion of the molecule due to concentration gradient (evaporation)

(Gariepy et al., 1989).

Donohue et al. (1989) described the permeability of asymmetric membranes as the volumetric flow of a gas across the membrane per unit area per unit time per unit pressure difference across the membrane (Donohue et al., 1989). The permeability of a polymer-based membrane depends on the polymeric chain structures and its interaction with gases. The permeability of a membrane tends to increase with an increase in its temperature and external pressure (Donohue et al., 1989; Ettouney, Al-Enezi, Hamam, & Hughes, 1994). Knowledge of the permeability of silicone-based membrane helps in its selection for modified atmosphere storage systems. The attribute of membrane which is commonly looked for its use in the storage of fresh fruits and vegetables is the high permeability for CO_2 and low permeability for O_2 (Gariepy et al., 1988). Hence, study of permeability is of importance in the silicon-based membrane systems.

Not many implementations of silicone membrane technology in postharvest storage have been reported in the literature. In order to fully utilize the potential of such systems, more research needs to be done on developing membrane-based systems for the storage of fresh fruits and vegetables. Silicone-based systems rely on the respiration rate of the stored produce, selectivity of the membrane to certain gases, and the properties of the membrane to maintain the atmosphere as desired inside the container. Table 6 lists the literature available on the use of silicone-based membrane for MA/CA storage of fruits and vegetables:

Table 6: List of studies on storage using silicone-based membrane systems available in the literature

Stored produce	**Literature**
Asparagus	(Gariepy, Raghavan, Castaigne, Arul, & Willemot, 1991; Li & Zhang, 2015)
Avocados	(Forero, 2007)
Bananas	(O. J. Stewart, Raghavan, Golden, & Gariepy, 2005)
Bell peppers	(González & Tiznado, 1993)
Cabbage	(Gariepy, Raghavan, & Theriault, 1984)
Carrot	(Reeleder, Raghavan, Monette, & Gariépy, 1989)
Celery	(Gariépy et al., 1986; Gariepy, Raghavan, Theriault, & Munroe, 1988)
Guava	(Sunjka, Nieuwenhof, & Raghavan, 2003)
Jackfruit	(Saxena, Bawa, & Srinivas Raju, 2008)
Kiwi	(Prabhanjan, Raghavan, Norris, & Gariepy, 1992)
Leek	(Gariépy, Raghavan, & Munroe, 1994; Gariepy et al., 1988)
Mushroom	(Li, Zhang, & Wang, 2007)
Onion	(Ravindra, Ambrose, Raghavan, & Annamalai, 2007)
Tomatoes	(Ravindra & Kailappan, 2007)

This chapter describes the investigation on the properties of five silicone-based membranes for their postharvest storage applications.

3.2 Materials and Methods

The silicone-based membranes used were provided by the Georgonne Plasticos company (Quebec, Canada), for studying their characteristics and find out the possible industrial-scale uses. Three different silicone-based membranes (coded as GA, GB, GC, Fig. 12), were provided by the company while two other silicone-based membranes were purchased from the market for comparison to the membranes supplied by the company. One of the two additional membranes was Marcellin (coded as MSM, Fig.11 (a)) membrane from France and the second one was a silicone-based membrane obtained from China (coded as CSM, Fig.11 (b)). All experiments to measure the properties of the membranes were performed in triplicate. In the Fig 11 and Fig. 12, 'top' surface denotes the surface of the membrane that is facing the ambient atmosphere and the 'bottom' denotes the suface attached to the lid and facing the atmosphere inside the conatiner.

Fig. 11: GA, GB, and GC membranes

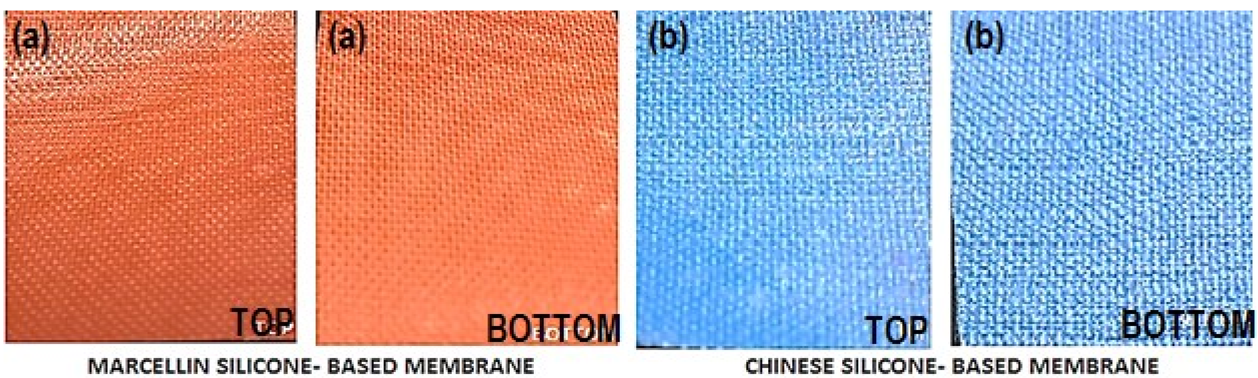

Fig. 12: (a) MSM and (b) CSM membranes

3.3 Physical properties

3.3.1 Surface analysis of the membranes

. The morphology of membranes was analysed by examination of their surface by using a scanning electron microscope (SEM) (JEOL Ltd., Tokyo, Japan). Silicone-based membranes have a silicone layer with a mesh-like nylon backing. For SEM analysis, a square piece of the silicone-based membrane (3 mm x 3mm) was taken. The specimen was placed on the specimen holder using a black carbon tape, no coating was applied on the silicone-based membrane. The examination was done at a 50X magnification using fast scan mode.

The thicknesses of the specimen membrane were measured at three random places of the narrow section of the membrane. The mean thickness was calculated and recorded.

3.3.2 Mechanical properties

The mechanical properties of the silicone-based membranes help understand their durability and for long-term use in storage. The tensile strength, Young's modulus, and elongation at break were measured using an Instron Universal Testing Machine (model 4500, Instron Corporation, Canton, MA). Dog-bone (I) shaped silicone-based membrane strips of 3.45 mm in width with 30 mm grip distance and no visible defects, were used to perform tensile strength analysis.

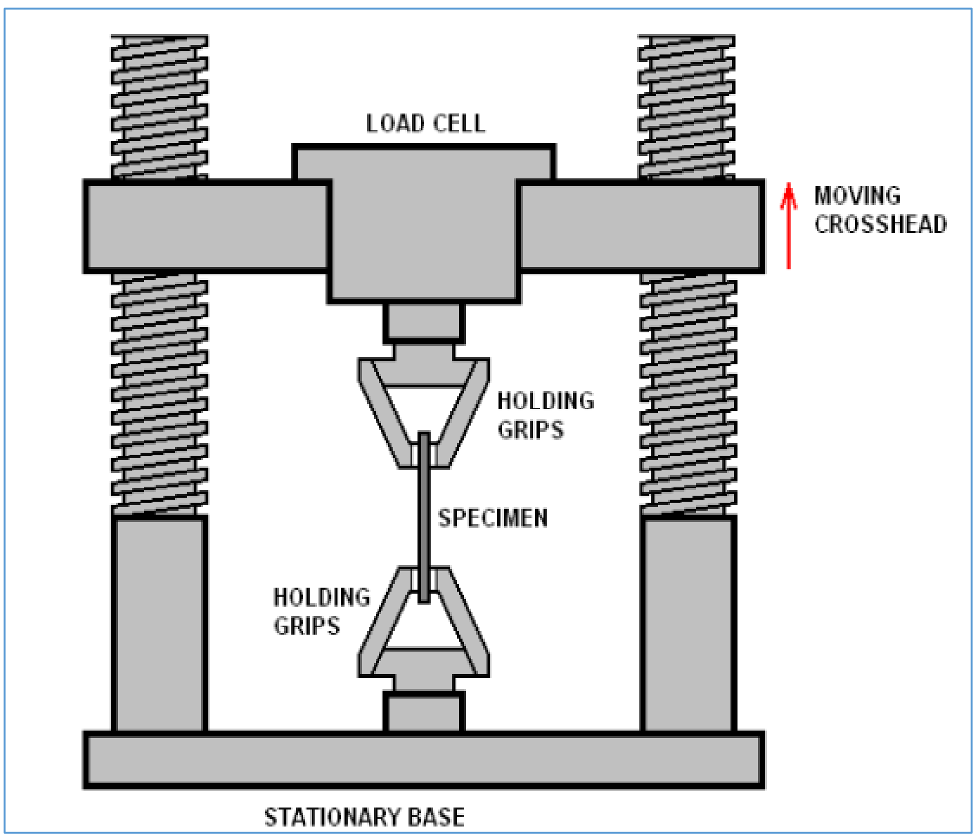

*Fig. 13:Schematic of Universal Testing Machine for Tensile strength analysis**

*Reprinted with permission from http://www.engineeringarchives.com/les_mom_tensiletest.html

Prior to the analysis of the membranes, they were conditioned to 50 % RH and 23 °C for 48 hours. The tests were conducted at a crosshead speed of 10 mm/min. and 500 N load cell was used. The measurements were done in triplicate and the average values and the standard deviations of the values were calculated.

3.3.3 Permeability

The permeability measurement of the silicone membranes was necessary to determine their usability in the modified storage systems. A system based on ASTM standard D1434-82, consisting of a glass Mason jar (1 L) was flushed with pure nitrogen gas and the silicone-based membrane with pre-determined area was used as a partition between the filled nitrogen gas and the ambient air (Fig. 14), for the measurement of the permeability of the membranes for O_2 gas (American Society for Testing and Materials, 2003). The membrane (MSM/CSM/GA/GB/GC) was placed as a window on the lid of the storage chamber. A septum was placed to take gas measurements at fixed intervals using a one ml syringe. For the measurement of the permeability of the membranes for CO_2, the container was enriched with carbon dioxide gas, and the silicone-based membrane with pre-determined area was used as a partition between the filled CO_2 gas and the ambient air.

The temperature was maintained constant and only negligible pressure difference was observed across the membrane throughout the experiments. Over time, due to the permeability of the membrane, change in gas concentration inside the container was observed, and was measured using gas chromatography. The time required to observe the substantial change in the concentration of gases varied between 4 to 6 hours for the MSM and CSM membranes and 48 hours for GA, GB, and GC membranes. These values of time were then used to estimate the permeability of the membrane, using the Equation (7) based on Henry's law.

$$P_{gas} = \frac{Q \cdot l}{A \cdot t \cdot \Delta p_{gas}} \tag{7}$$

Where,

P_{gas} = permeability to the gas

Q = moles of gas transferred across membrane

l = thickness of the membrane (m)

A = area of membrane (m^2)

t = duration of the experiment

Δp_{gas} = partial pressure difference across membrane for a particular gas

A gas chromatograph with electronic integrator (SRI 8610 Instruments, California, USA) fitted with a thermal conductivity detector (TCD) was used for gas analysis.

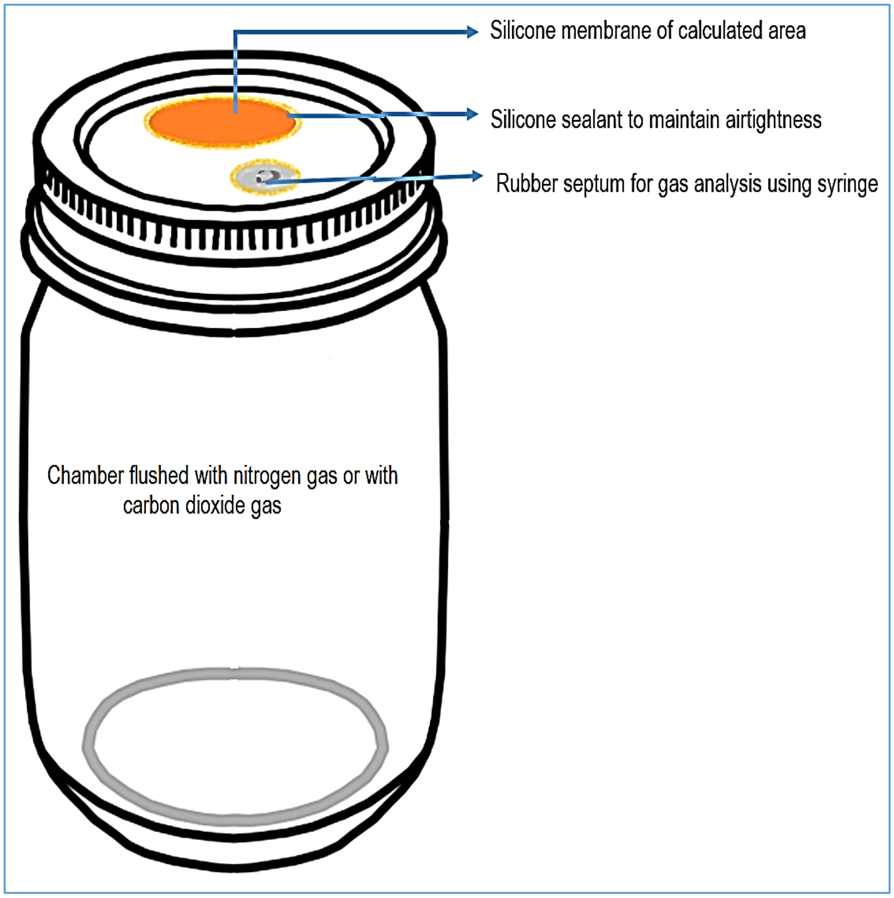

Fig. 14: Setup used for permeability measurement

Helium gas was used as the mobile phase at 4.76 atm pressure. The oven temperature was fixed at 45 °C and the detector temperature set at 120 °C. The data was recorded and analysed using the Peak Simple Chromatograph Data System Software for Windows (SRI Instruments, California, USA). Three gas samples of 0.10 ml were extracted from each flushed container and injected into sample injecting port of the gas chromatograph. The instrument was calibrated before analysis with the standard gas of known concentration. Retention time was set to 4 min. and it was assumed that the samples comprised only CO_2, N_2, and O_2 gases. The mean and the standard deviation values of the gas concentration were calculated. The results were used to determine the permeability of the membranes.

3.3.4 Selectivity in gas transmission

Selectivity of the membrane for a particular is derived from the gas transmission rate. Silicone-based membranes are selectively permeable to certain gases i.e. they tend to have a higher permeability for CO_2 as compared to O_2 gas. The selectivity ratio is an important factor in the selection of membranes used for controlled or modified atmosphere storage.

Hence, along with the permeability calculations, the selectivity ratios of the silicone-based membranes, particularly the ratio for CO_2:O_2 and CO_2:N_2 were determined.

Selectivity ratios were calculated as follows:

$$Selectivity\left(\frac{CO_2}{O_2}\right) = \frac{P_{CO2}}{P_{O2}} \tag{8}$$

Where,

P_{co2} = permeability to CO_2 in CO_2 enriched container

P_{o2} = permeability to O_2 in N_2 flushed container

3.4 Results and Discussion

3.4.1 Surface analysis of membranes

The SEM analysis of the silicone-based membranes helped to understand the uniformity of membrane at the microscopic level. The micrographs were taken at a magnification of 50X for the top and bottom surface of the membranes. The Chinese silicone-based membrane showed an uneven top surface with a patchy backing (Fig. 15). The MSM membrane has a smooth surface on both sides with less visible patches (Fig. 16).

The GA, GB, and GC silicone-based membranes have a smooth even top surface with no visible markings (Fig. 15–19). The bottom surface of the GA membrane was tightly woven with uniform distribution of the fibers, whereas the on the GB membrane, and the underside has uneven fibre weaving. The GC membrane has pretty uniformly weaved backing and wasn't very dense.

The thickness of the membranes was measured at three different points for each membrane. Average thickness and standard deviation for MSM was 0.197 ± 0.005 mm, CSM was 0.257 ± 0.009 mm, GA was 0.133 ± 0.005 mm, GB was 0.203 ± 0.012 mm, GC was 0.123 257 ± 0.009 mm.

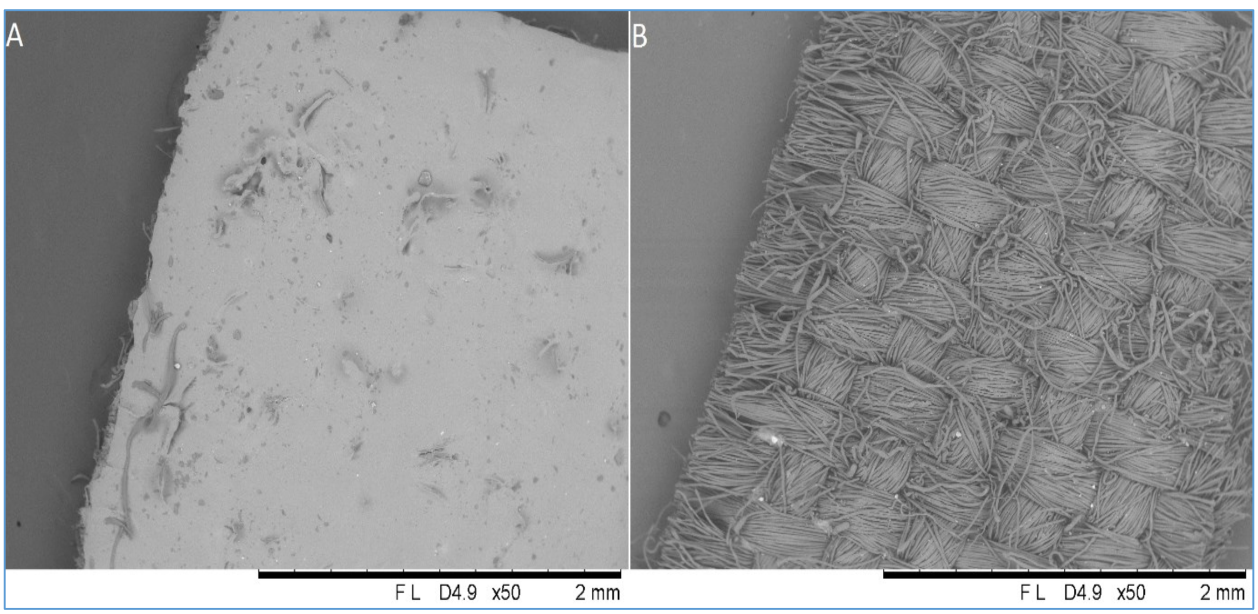

Fig. 15: SEM micrograph of CSM as observed at 50X magnification (A-top-facing surface and B-bottom-facing surface)

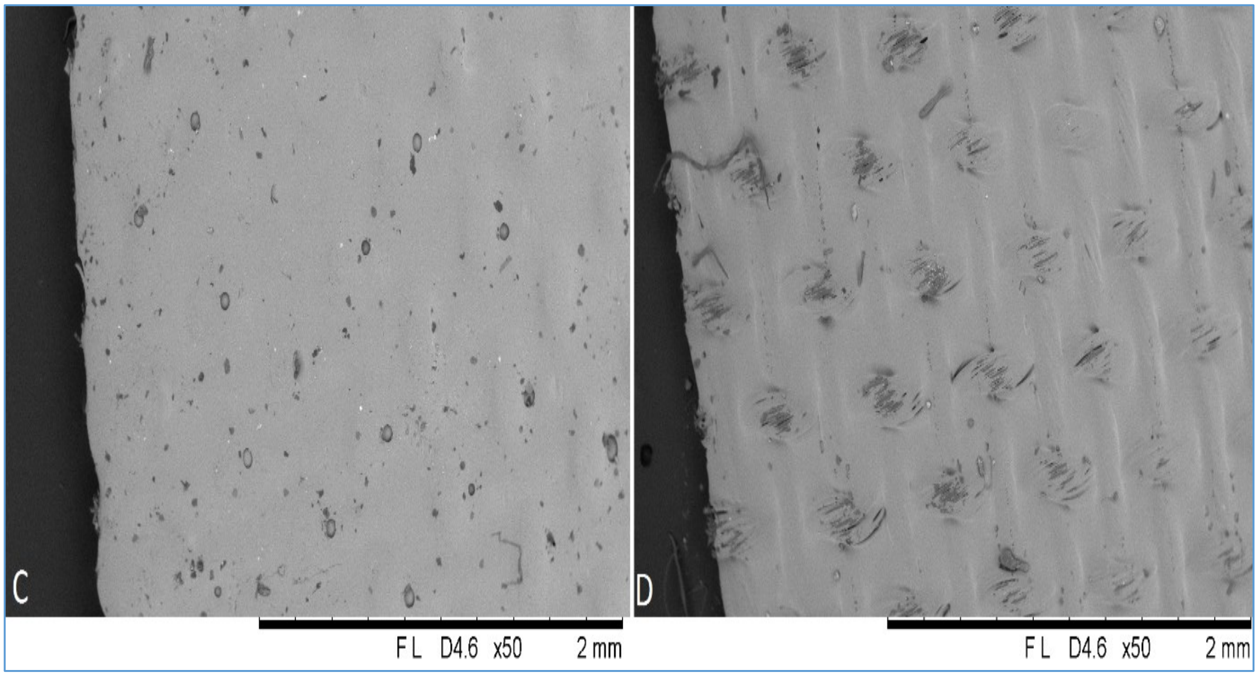

Fig. 16: SEM micrograph of MSM as observed at 50X magnification (C-top-facing surface and D-bottom-facing surface)

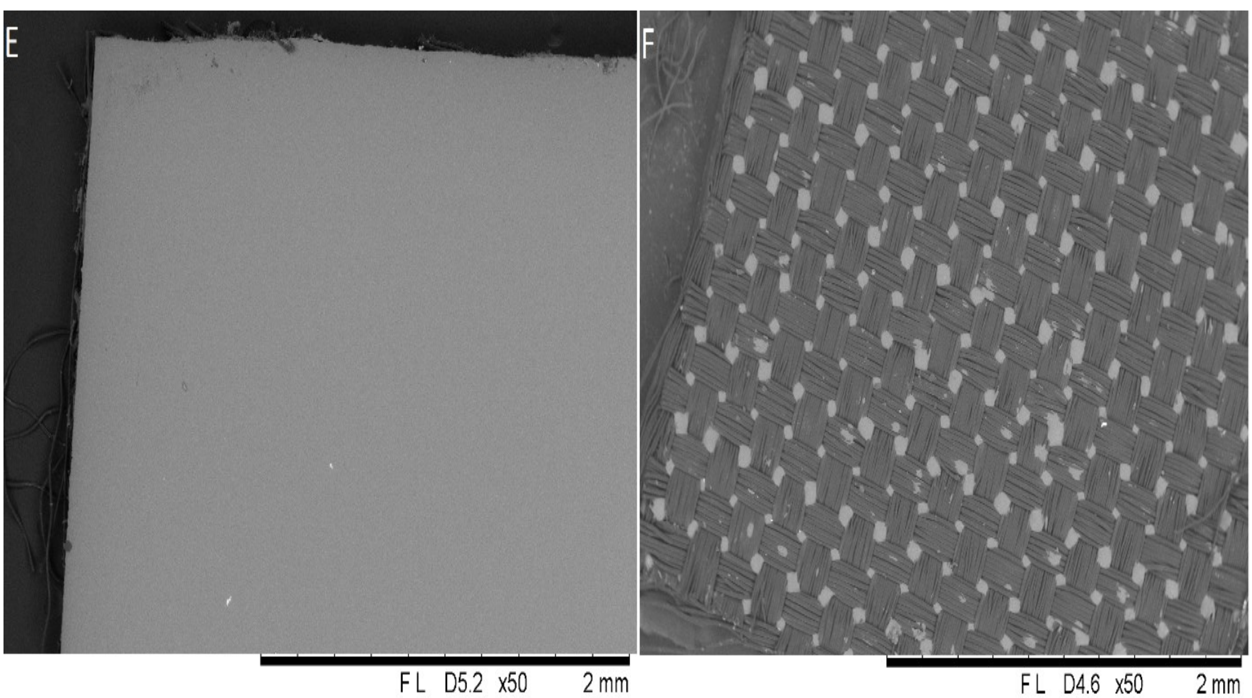

Fig. 17: SEM micrograph of GA membrane as observed at 50X magnification (E-top-facing surface and F-bottom-facing surface)

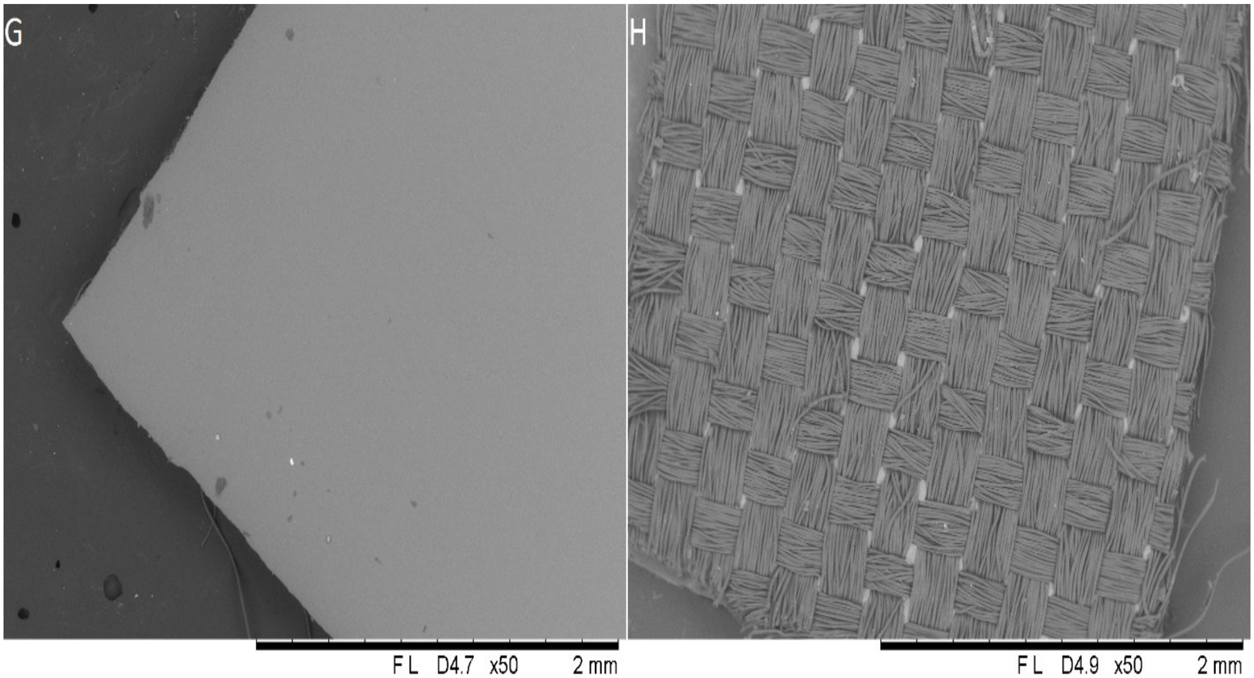

Fig. 18: SEM micrograph of GB membrane as observed at 50X magnification (G-top-facing surface and H-bottom-facing surface)

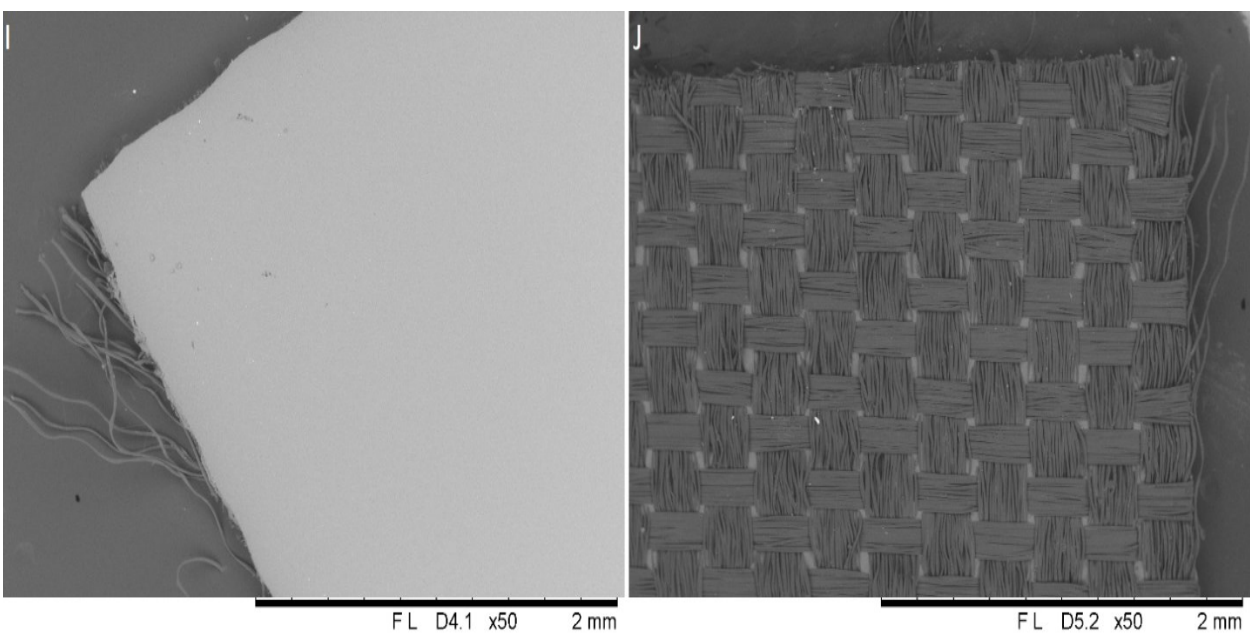

Fig. 19: SEM micrograph of GC membrane as observed at 50X magnification (I-top-facing surface and J-bottom-facing surface)

3.4.2 Tensile strength, Young's modulus, Elongation at break point

The five different membranes had shown different behaviors under tension, emphasizing the difference in their mechanical properties. The mechanical properties of the silicone-based membranes are shown in Table 7. The CSM membrane was able to withstand a higher load before breaking at a value of 151.7 MPa, showing its higher tensile strength than the other silicone-based membranes.

*Table 7: Mechanical properties of Silicone-based membranes**

Membrane type	Tensile strength/ Max load (MPa)	Elongation at break (mm)	Young's modulus (MPa)	Energy at break point (J)
MSM	37.580 ± 2.088ab	6.594 ± 0.274	168.428 ± 14.277	0.159 ± 0.018
CSM	151.724 ± 12.383	5.176 ± 0.012	641.218 ± 70.016	0.239 ± 0.011c
GA	76.889 ± 6.149a	12.837 ± 0.631	107.623 ± 7.096	0.302 ± 0.034
GB	60.430 ± 1.554	14.133 ± 0.414	65.872 ± 1.371	0.404 ± 0.023
GC	70.000 ± 5.312b	10.500 ± 0.410	98.040 ± 7.838	0.252 ± 0.038c

**Each observation is mean ± S.D (n=3). The Same letter beside a mean value indicates that they are not significantly different according to Fisher's L.S.D. test (α=0.05).*

Measured tensile strength values of the CSM membrane signified the strength of the nylon backing rather than the silicone film. It was observed that the CSM had the highest value of Young's modulus where as the GB had the lowest value, indicating its delicate nature. The GA and the GC membranes exhibited similar properties for all the measured characteristics. Previous studies by Gariepy et al. (1989), have shown that MSM is anisotropic in nature i.e. the mechanical properties vary depending on the direction of the force vector applied (Gariepy & Raghavan, 1989). The GB membrane has absorbed the highest amount of energy before yielding, supporting the observed Young's modulus value. In fresh fruit and vegetable storage, membranes need to have good stretch ability and sturdiness.

The data of load (N) vs. displacement (mm) for membranes helps to identify the maximum load supported before yielding. All data was collected in triplicate and is shown in Fig. 20-24.

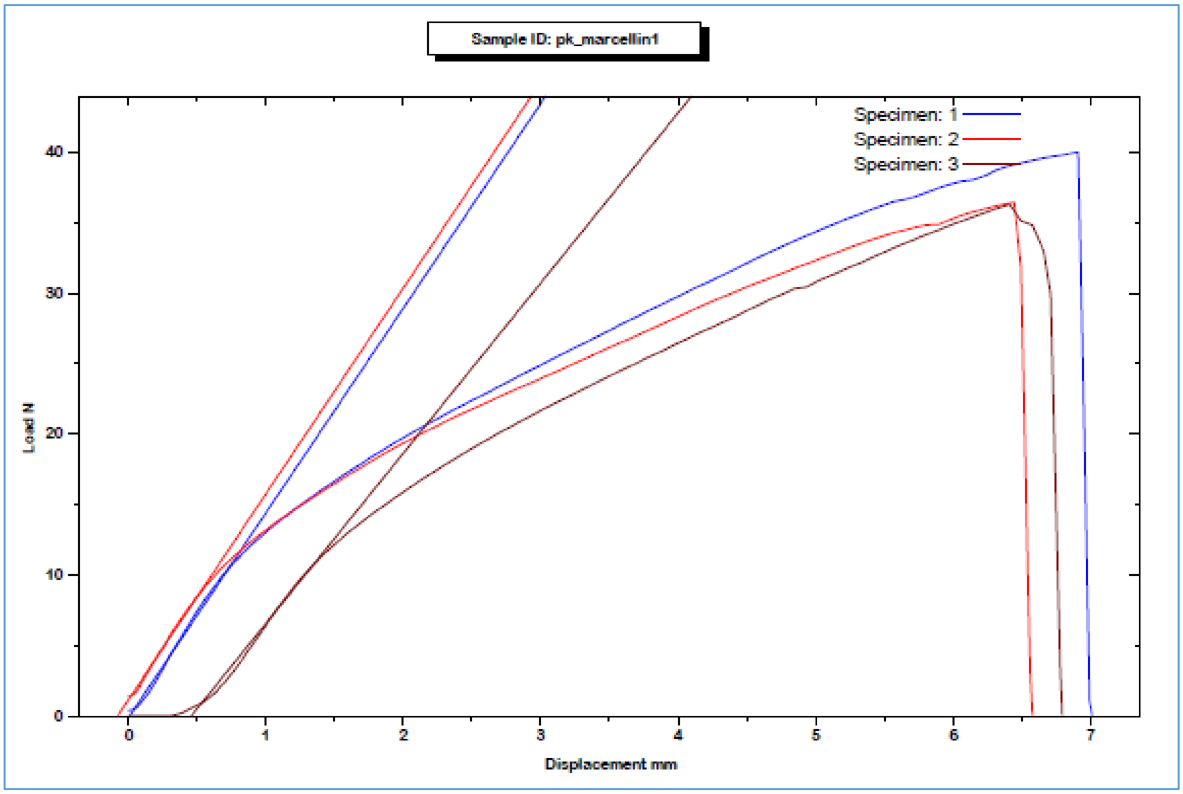

Fig. 20: Load vs. displacement curve for MSM

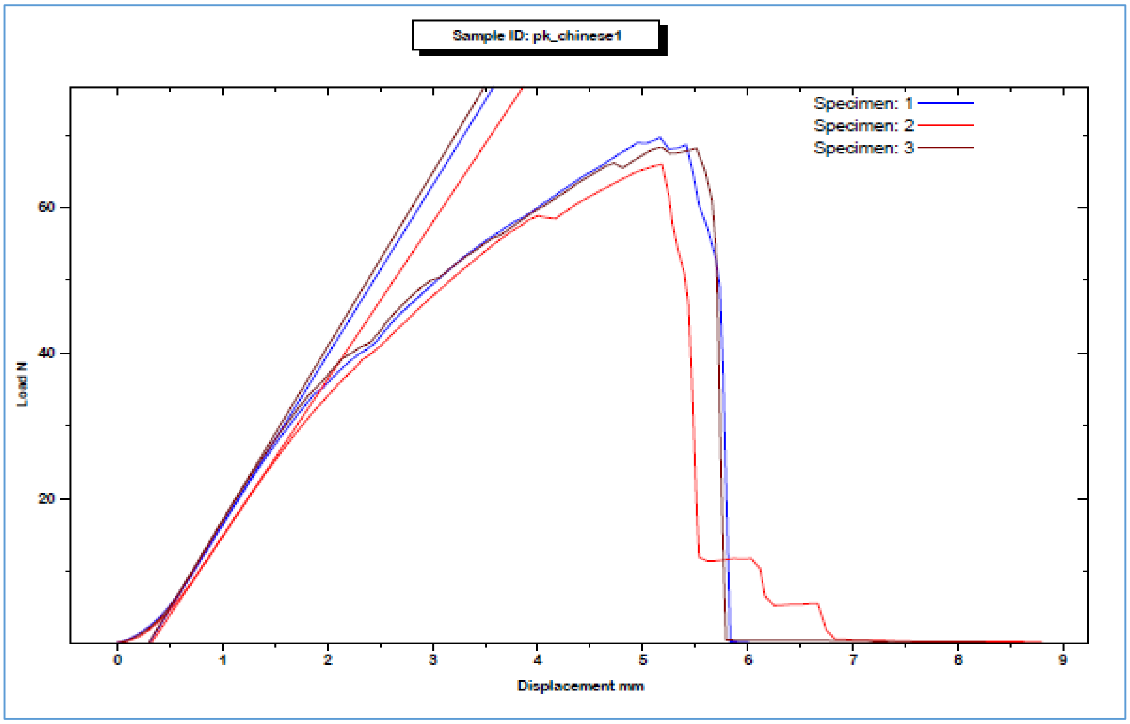

Fig. 21: Load vs. displacement curve for CSM

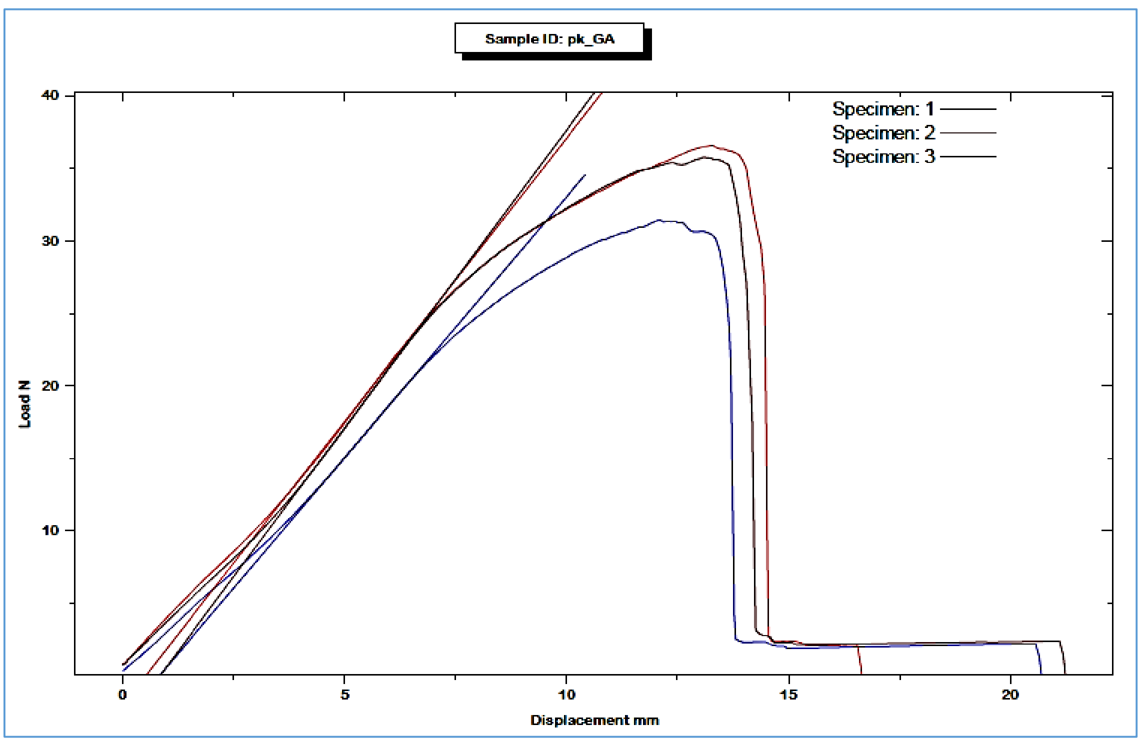

Fig. 22: Load vs. displacement curve for GA membrane

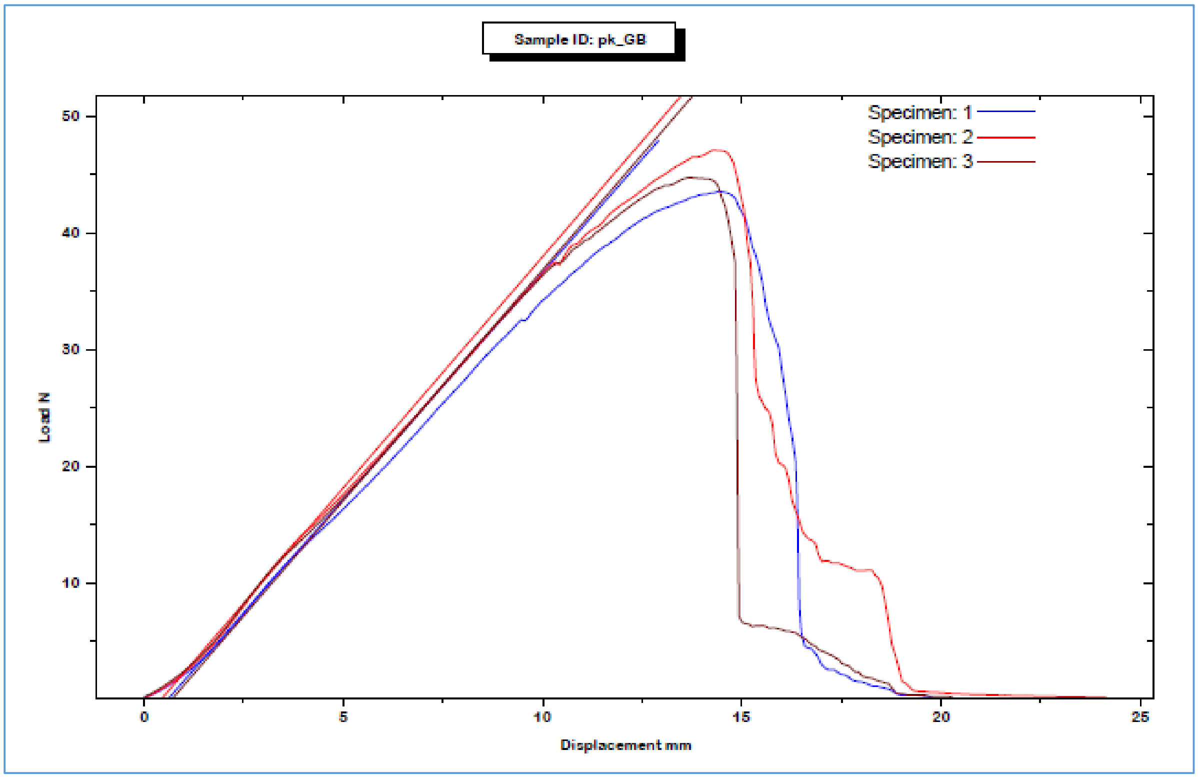

Fig. 23: Load vs. displacement curve for GB membrane

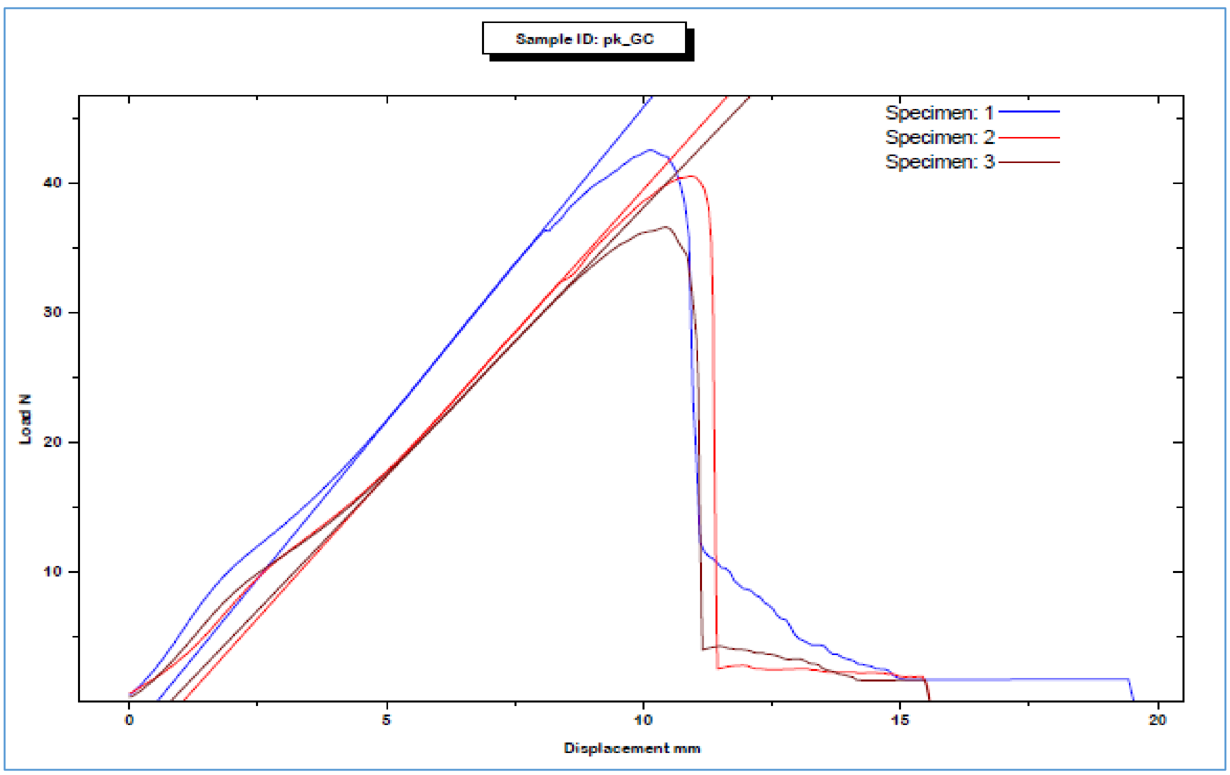

Fig. 24: Load vs. displacement curve for GC membrane

3.4.3 Permeability

The permeability of the membrane is one of the deciding factors for its suitability in long-term storage of produce. Permeability was determined as per the procedure and calculations previously mentioned (and the observed values given in Table 8). All the measurements were taken at room temperature and at standard atmospheric pressure. The gas transmission rates for CO_2, N_2 and O_2 were measured separately for each of the membranes. Noticeable changes in pressure inside the chamber wasn't observed, hence wasn't considered as relevant in the calculations.

Table 8: Permeability of the various membranes studied, flushed with CO_2 and flushed with N_2

TYPE	P(CO_2)	P(O_2)	P(N_2)
	l/m²-Atm-d	l/m²-Atm-d	l/m²-Atm-d
MARCELLIN	1577.6	272.5	273
CO_2 FLUSH	1577.6	835.1	1753.5
N_2 FLUSH	1063.6	272.5	273
CHINESE	3332.2	1349.5	1351.8
CO_2 FLUSH	3332.2	6714.9	3215.2
N_2 FLUSH	7931	1349.5	1351.8
GA	621.43	197.25	198.05
CO_2 FLUSH	621.4333	628.1667	617.4667
N_2 FLUSH	1507.8	197.25	198.05
GB	703.63	432.43	431.67
CO_2 FLUSH	703.6333	288.2667	1343.167
N_2 FLUSH	714	432.4333	431.6667
GC	825.87	279.13	276.8
CO_2 FLUSH	825.8667	904.3	805.1667
N_2 FLUSH	183.9667	279.1333	276.8

The storage cylinder was flushed with carbon dioxide resulting in higher CO_2 levels inside the container. This gave an accurate CO_2 permeability value for the membrane tested. When the container was flushed with nitrogen gas, the concentration of nitrogen and oxygen in the container was higher. Hence, permeability values calculated from nitrogen flushing method were used as membrane permeability to oxygen, and nitrogen gas.

As observed from the Table 8, the CSM had the highest permeability to CO_2, N_2, and O_2 which may be attributed to its unevenly weaved nylon backing. Since, the Marcellin and Chinese membranes were used as reference membranes for assisting in the selection among the GA, GB, and GC membranes, they were used in further experiment also. Among the membranes provided by the Georgonne Plasticos, the GC membrane had the highest permeability to carbon dioxide which is favorable for the storage of fresh produce. Higher permeability to carbon dioxide and lower permeability to oxygen are essential in membrane-based storage systems. When a commodity is stored in a closed system, almost all the oxygen present will be consumed for the respiration of the stored product. The respiration and the consumption of the glucose and the resulting metabolites leads to the eventual decay of the perishable product.

Using a membrane with high CO_2 permeability and low O_2 permeability, a steady gas exchange occurs at the interface between the atmosphere and the gases present in the storage chamber. The silicone-based membrane acts as this interface and maintains low oxygen concentration and high carbon dioxide concentration in the storage chamber, which could lead to enhanced storage life.

3.4.4 Selectivity in gas transmission

Silicone-based membranes are primarily known for their varying selectivity ratios for atmospheric gases. Generally, they have higher selectivity to carbon dioxide as compared to oxygen or nitrogen. This is due to high permeability to CO_2 and low permeability to oxygen, and nitrogen. Selectivity ratios were calculated using the permeability values from Table 8 using the Equation (8) and are shown in Table 9.

Table 9: Selectivity ratios of the different membranes

Membrane type	Selectivity ($CO_2 : O_2$)	Selectivity ($CO_2 : N_2$)
MSM	5.8	5.8
CSM	2.5	2.5
GA	3.2	3.1
GB	1.6	1.6
GC	3.0	3.0

The MSM has shown the highest selectivity ratios for carbon dioxide to oxygen gas and carbon dioxide to nitrogen gas. This suggests that when the MSM membrane is used, the exchange of CO_2 across the membrane will be higher than O_2 and N_2. A higher CO_2 concentration signals the plant material to reduce the respiration activity and slow down unnecessary metabolic activities. Since the GB membrane has the least selectivity ratios, it wasn't used for further studies. The GA membrane had similar selectivity ratios as that of the GC membrane, but the GC membrane had a higher permeability to CO_2 than that of the GA membrane, therefore was selected for further storage studies.

3.5 Concluding Remarks

The surface characterisation of the membranes showed that the CSM membrane had the highest thickness value of 0.257 ± 0.009 mm and had an uneven surface. The membranes obtained from Georgonne Plasticos had lower thicknesses and had a smooth surface and evenly weaved nylon backing.

Since, the use of membrane-based storage systems for long-term storage of fresh produce needs to be explored for large scale use, mechanical properties of the membrane were studied. The CSM membrane showed highest tensile strength of 151.7 MPa before breaking signifying the strength of the nylon backing rather than the silicone membrane.

The membrane should have high permeability to carbon dioxide and high selectivity ratios of carbon dioxide to oxygen and carbon dioxide to nitrogen. Out of the five membranes studied, the CSM membrane had the highest CO_2 permeability equal to 3332.2 L m^{-2} atm^{-1} day^{-1} followed by the MSM membrane with a CO_2 permeability of 1577.6 L m-^{2} atm^{-1} day^{-1}. The MSM membrane showed highest selectivity ratios among the five membranes studied.

3.6 Acknowledgements

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) and Georgonne Plasticos (Quebec, Canada). The authors would like to thank Dr. Darwin Lyew for providing insight and expertise, and timely advice that greatly assisted the research.

References

Abd Allah, E. S. H., Makboul, R., & Mohamed, A. O. (2016). Role of serotonin and nuclear factor-kappa B in the ameliorative effect of ginger on acetic acid-induced colitis. *Pathophysiology, 23*(1), 35-42. doi: 10.1016/j.pathophys.2015.12.001

Abdel-Naeem, H. H. S., & Mohamed, H. M. H. (2016). Improving the physico-chemical and sensory characteristics of camel meat burger patties using ginger extract and papain. *Meat Science, 118*, 52-60. doi: 10.1016/j.meatsci.2016.03.021

Afek, U., & Kays, S. J. (2004). Postharvest physiology and storage of widely used root and tuber crops. *Hort Rev, 30*, 253-318.

Directorate of Marketing and Inspection (2005). Spice Grading and Marking Rules, India.

Agudo, J. E., Pardo, P. J., Sánchez, H., Pérez, Á. L., & Suero, M. I. (2014). A low-cost real color picker based on arduino. *Sensors, 14*(7), 11943-11956.

Akamine, E. K. (1977). Tropical and subtropical crops in Hawaii. *CSIRO Food Research Quarterly, 37*(1), 13-20.

Ali, B. H., Blunden, G., Tanira, M. O., et al. (2008). Some phytochemical, pharmacological and toxicological properties of ginger (Zingiber officinale Roscoe): a review of recent research. *Food Chem Toxicol, 46*(2), 409-420. doi:10.1016/j.fct.2007.09.085

An, K., Zhao, D., Wang, Z., et al. (2016). Comparison of different drying methods on Chinese ginger (Zingiber officinale Roscoe): Changes in volatiles, chemical profile, antioxidant properties, and microstructure. *Food Chemistry, 197, Part B*, 1292-1300. doi: 10.1016/j.foodchem.2015.11.033

American Society for Testing and Materials (ASTM) (2003) Standard test method for determining gas permeability characteristics of plastic film and Sheeting. Annual book of ASTM standards.

Baliga, M. S., Haniadka, R., Pereira, et al. (2011). Update on the Chemopreventive Effects of Ginger and its Phytochemicals. *Critical Reviews in Food Science and Nutrition, 51*(6), 499-523. doi:10.1080/10408391003698669

Baliga, M. S., Latheef, L., Haniadka, R., et al. (2013). Chapter 41 - Ginger (Zingiber officinale Roscoe) in the Treatment and Prevention of Arthritis A2 - Watson, Ronald Ross. In V. R. Preedy (Ed.), *Bioactive Food as Dietary Interventions for Arthritis and Related Inflammatory Diseases* (pp. 529-544). San Diego: Academic Press.

Bandyopadhyay, M., Chakraborty, R., & Raychaudhuri, U. (2007). A process for preparing a natural antioxidant enriched dairy product (Sandesh). *Lwt-Food Science and Technology, 40*(5), 842-851. doi:10.1016/j.lwt.2006.05.007

Barrett, D. M., Somogyi, L., & Ramaswamy, H. S. (2004). *Processing Fruits: Science and Technology, Second Edition*: CRC Press.

Beaudry, R. M. (1999). Effect of O2 and CO2 partial pressure on selected phenomena affecting fruit and vegetable quality. *Postharvest Biology and Technology, 15*(3), 293-303. doi: 10.1016/S0925-5214(98)00092-1

Bodbodak, S., & Moshfeghifar, M. (2016). 2 - Advances in controlled atmosphere storage of fruits and vegetables A2 - Siddiqui, Mohammed Wasim *Eco-Friendly Technology for Postharvest Produce Quality* (pp. 39-76): Academic Press.

Britannica, E. (2016). Ginger. Available at: http://academic.eb.com/levels/collegiate/article/36862 [Last accessed on 20 June 2016].

Butler, E. J. (1907). *An account of the genus Pythium and some Chytridiaceae*: Thacker.

Paull, R. E. & Chen, C. C. (2014). *Ginger* USDA (Ed.) *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*

Chong, K. L., Peng, N., Yin, H., et al. (2013). Food sustainability by designing and modelling a membrane controlled atmosphere storage system. *Journal of Food Engineering, 114*(3), 361-374. doi:10.1016/j.jfoodeng.2012.08.027

Chung, H.-S., & Moon, K.-D. (2011). Sprouting and quality control of fresh ginger rhizomes by modified atmosphere packaging with film perforation. *Food Science and Biotechnology, 20*(3), 621-627. doi:10.1007/s10068-011-0088-4

Donohue, M. D., Minhas, B. S., & Lee, S. Y. (1989). Permeation behavior of carbon dioxide-methane mixtures in cellulose acetate membranes. *Journal of Membrane Science, 42*(3), 197-214. doi: 10.1016/S0376-7388(00)82376-5

Embuscado, M. E. (2015). Spices and herbs: Natural sources of antioxidants – a mini review. *Journal of Functional Foods, 18, Part B*, 811-819. doi: 10.1016/j.jff.2015.03.005

Ettouney, H. M., Al-Enezi, G., Hamam, S. E. M., et al. (1994). Characterization of the permeation properties of CO2, N2 gas mixtures in silicone rubber membranes. *Gas Separation & Purification, 8*(1), 31-36. doi:10.1016/0950-4214(94)85005-4

The State of Food Insecurity in the World (2013) Multiple Dimensions of Food Security, FAO. http://www.fao.org/docrep/018/i3434e/i3434e00.htm [last accessed on 13 July 2016].

Farber, J. N., Harris, L. J., Parish, M. E., et al. (2003). Microbiological Safety of Controlled and Modified Atmosphere Packaging of Fresh and Fresh-Cut Produce. *Comprehensive Reviews in Food Science and Food Safety, 2*, 142-160. doi:10.1111/j.1541-4337.2003.tb00032.x

Figoli, A., De Luca, G., & Drioli, E. (2007). Polymeric capsule production for food packaging application. *Italian journal of food science, 19*, 90-96.

Finnegan, E., Mahajan, P. V., O'Connell, M., et al. (2013). Modelling respiration in fresh-cut pineapple and prediction of gas permeability needs for optimal modified atmosphere packaging. *Postharvest Biology and Technology, 79*, 47-53. doi: 10.1016/j.postharvbio.2012.12.015

Fonseca, S. C., Oliveira, F. A. R., & Brecht, J. K. (2002). Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: a review. *Journal of Food Engineering, 52*(2), 99-119. doi: 10.1016/S0260-8774(01)00106-6

Food, & Agriculture Organization of the United, N. (2014). FAOSTAT.

Forero, M. P. (2007). Storage life enhancement of avocado fruits. (Master's dissertation), McGill University.

Funk, J. L., Frye, J. B., Oyarzo, J. N., et al. (2016) Anti-Inflammatory Effects of the Essential Oils of Ginger (Zingiber officinale Roscoe) in Experimental Rheumatoid Arthritis. *PharmaNutrition*. doi: 10.1016/j.phanu.2016.02.004

Gariepy, Y., Munroe, J. A., Raghavan, G. S. V., et al. (1987) Data acquisition and control of storage environment *Paper, American Society of Agricultural Engineers; 1987. (87-4070):23pp. 11 ref.*

Gariepy, Y., & Raghavan, G. S. V. (1989) A mathematical model for a pressure regulated silicone membrane gas permeator for CA storage *Paper - American Society of Agricultural Engineers; 1989. (89-4049):16 pp. 16 ref.*

Gariepy, Y., Raghavan, G. S. V., Castaigne, F., et al. (1991). Precooling and modified atmosphere storage of green asparagus. *Journal of Food Processing and Preservation, 15*(3), 215-224.

Gariépy, Y., Raghavan, G. S. V., & Munroe, J. A. (1994). Long-term storage of leek stalks under regular and controlled atmospheres. *International Journal of Refrigeration, 17*(2), 140-144. doi: 10.1016/0140-7007(94)90056-6

Gariepy, Y., Raghavan, G. S. V., & Theriault, R. (1984). Use of the membrane system for long-term CA storage of cabbage. *Canadian Agricultural Engineering, 26*(2), 105-109.

Gariépy, Y., Raghavan, G. S. V., & Thériault, R. (1986). Controlled atmosphere storage of celery with the silicone membrane system. *International Journal of Refrigeration, 9*(4), 234-239. doi: 10.1016/0140-7007(86)90096-4

Gariepy, Y., Raghavan, G. S. V., Theriault, R., & Munroe, J. A. (1988). Design procedure for the silicone membrane system used for controlled atmosphere storage of leeks and celery. *Canadian Agricultural Engineering, 30*(2), 231-236.

Gopala Rao, C. (2015). Chapter 33 - Equipment for Producing and Regulating Controlled Atmosphere. In C. G. Rao (Ed.), *Engineering for Storage of Fruits and Vegetables* (pp. 583-598): Academic Press.

Govindarajan, V. S. (1982). Ginger--chemistry, technology, and quality evaluation: part 1. *Crit Rev Food Sci Nutr, 17*(1), 1-96. doi:10.1080/10408398209527343

Gross, K. C., Wang, C. Y. & Salveit, M. (2014). The commercial storage of fruits, vegetables, and florist and nursery stocks. United, States Agricultural Research, Service.

Gümüşay, Ö. A., Borazan, A. A., Ercal, N., & Demirkol, O. (2015). Drying effects on the antioxidant properties of tomatoes and ginger. *Food Chemistry, 173*, 156-162. doi: 10.1016/j.foodchem.2014.09.162

Hubert, B., Rosegrant, M., van Boekel, M. A. J. S., et al. (2010). The Future of Food: Scenarios for 2050. *Crop Science, 50*(Supplement_1), S-33-S-50. doi:10.2135/cropsci2009.09.0530

Jacob, J. N. (2016). Chapter 4 - Comparative Studies in Relation to the Structure and Biochemical Properties of the Active Compounds in the Volatile and Nonvolatile Fractions of Turmeric (C. longa) and Ginger (*Z. officinale*). In R. Atta ur (Ed.), *Studies in Natural Products Chemistry* (Vol. Volume 48, pp. 101-135): Elsevier.

Jakribettu, R. P., Boloor, R., Bhat, H. P., et al. (2016). Chapter 50 - Ginger (Zingiber officinale Rosc.) Oils A2 - Preedy, Victor R *Essential Oils in Food Preservation, Flavor and Safety* (pp. 447-454). San Diego: Academic Press.

Kader, A., Lipton, W. J., & Morris, L. (1973). Systems for scoring quality of harvested lettuce. *HortSci*.

Kader, A. A. (2004). *Increasing food availability by reducing postharvest losses of fresh produce.* Paper presented at the V International Postharvest Symposium 682.

Kader, A. A., Zagory, D., & Kerbel, E. L. (1989). Modified atmosphere packaging of fruits and vegetables. *Crit Rev Food Sci Nutr, 28*(1), 1-30. doi:10.1080/10408398909527506

Kaur, K., Saxena, A., Haniadka, R., et al. (2015). Chapter 6 - Medicinal Benefits of Ginger in Various Gastrointestinal Ailments: Use in Geriatric Conditions A2 - Watson, Ronald Ross *Foods and Dietary Supplements in the Prevention and Treatment of Disease in Older Adults* (pp. 51-61). San Diego: Academic Press.

Kawamoto, Y., Ueno, Y., Nakahashi, E., et al. (2016). Prevention of allergic rhinitis by ginger and the molecular basis of immunosuppression by 6-gingerol through T cell inactivation. *The Journal of Nutritional Biochemistry, 27*, 112-122. doi: 10.1016/j.jnutbio.2015.08.025

Kays, S. J. (1991). *Postharvest physiology and handling of perishable plant products*: Van Nostrand Reinhold Inc.

Kim, D.-H., & Lee, Y.-C. (2006). Changes in some quality factors of frozen ginger as affected by the freezing storage conditions. *JSFA Journal of the Science of Food and Agriculture, 86*(10), 1439-1445.

Kirkland, B. S., Clarke, R., & Paul, D. R. (2008). A versatile membrane system for bulk storage and shipping of produce in a modified atmosphere. *Journal of Membrane Science, 324*(1–2), 119-127. doi: 10.1016/j.memsci.2008.07.001

Kok, R., & Raghavan, G. S. V. (1982). A Mathematical Model of the Controlled Atmosphere Storage of Apples Using The Marcellin System. *Canadian Institute of Food Science and Technology Journal, 15*(3), xvi. doi: 10.1016/S0315-5463(82)72451-4

Konar, E. M., Harde, S. M., Kagliwal, L. D., et al. (2013). Value-added bioethanol from spent ginger obtained after oleoresin extraction. *Industrial Crops and Products, 42*, 299-307. doi: 10.1016/j.indcrop.2012.05.040

Le, D. P., Smith, M., Hudler, G. W., et al. (2014). Pythium soft rot of ginger: Detection and identification of the causal pathogens, and their control. *Crop Protection, 65*, 153-167. doi: 10.1016/j.cropro.2014.07.021

Lee, Y. B., Kim, Y. S., & Ashmore, C. R. (1986). Antioxidant Property in Ginger Rhizome and Its Application to Meat Products. *Journal of Food Science, 51*(1), 20-23. doi:10.1111/j.1365-2621.1986.tb10826.x

Letizia, C. S., Cocchiara, J., Lalko, J., et al. (2003). Fragrance material review on linalool. *Food and Chemical Toxicology, 41*(7), 943-964. doi: 10.1016/S0278-6915(03)00015-2

Liplap, P., Boutin, J., LeBlanc, D. I., et al. (2014). Effect of hyperbaric pressure and temperature on respiration rates and quality attributes of Boston lettuce. *International Journal of Food Science & Technology, 49*(1), 137-145. doi:10.1111/ijfs.12288

Lopresto, C. G., Petrillo, F., Casazza, A. A., et al. (2014). A non-conventional method to extract D-limonene from waste lemon peels and comparison with traditional Soxhlet extraction. *Separation and Purification Technology, 137*, 13-20. doi: 10.1016/j.seppur.2014.09.015

Lu, M., Yuan, B., Zeng, M., & Chen, J. (2011). Antioxidant capacity and major phenolic compounds of spices commonly consumed in China. *Food Research International, 44*(2), 530-536. doi: 10.1016/j.foodres.2010.10.055

Majidi, H., Minaei, S., Almassi, M., et al. (2014). Tomato quality in controlled atmosphere storage, modified atmosphere packaging and cold storage. *Journal of Food Science and Technology, 51*(9), 2155-2161. doi: 10.1007/s13197-012-0721-0

Martínez-Romero, D., Guillén, F., Castillo, S., et al. (2009). Effect of ethylene concentration on quality parameters of fresh tomatoes stored using a carbon-heat hybrid ethylene scrubber. *Postharvest Biology and Technology, 51*(2), 206-211. doi: 10.1016/j.postharvbio.2008.07.011

Mattos, L. M., Moretti, C. L., Jan, S., et al. (2014). Chapter 19 - Climate Changes and Potential Impacts on Quality of Fruit and Vegetable Crops. In P. Ahmad & S. Rasool (Eds.), *Emerging Technologies and Management of Crop Stress Tolerance* (pp. 467-486). San Diego: Academic Press.

McGuire, R. G. (1992). Reporting of objective color measurements. *HortScience, 27*(12), 1254-1255.

Misawa, K., Hashizume, K., Yamamoto, M., et al. (2015). Ginger extract prevents high-fat diet-induced obesity in mice via activation of the peroxisome proliferator-activated receptor δ pathway. *The Journal of Nutritional Biochemistry, 26*(10), 1058-1067. doi: 10.1016/j.jnutbio.2015.04.014

Morris, R. F. (1978). Postharvest food losses in developing countries: a bibliography: National Academies.

Mukherjee, P. K., Thomas, P., & Raghu, K. (1995). Shelf-life enhancement of fresh ginger rhizomes at ambient temperatures by combination of gamma-irradiation, biocontrol and closed polyethylene bag storage. *Annals of Applied Biology, 127*(2), 375-384. doi:10.1111/j.1744-7348.1995.tb06681.x

Naik, R., Ambrose, D. C. P., Raghavan, G. S. V., et al. (2014). Enhancing shelf life of minimally processed multiplier onion using silicone membrane. *Journal of Food Science and Technology-Mysore, 51*(12), 3963-3969. doi:10.1007/s13197-012-0898-2

Nair, K. P. P. (2013). 23 - The Postharvest and Industrial Processing of Ginger *The Agronomy and Economy of Turmeric and Ginger* (pp. 433-452). Oxford: Elsevier.

Natarajan, C. P., Bai, R. P., Krishnamurthy, M. N., et al. (1972). Chemical composition of ginger varieties and dehydration studies on ginger. *Journal of Food Science and Technology, India, 9*(3), 120-124.

National Center for, C., & Alternative, M. (2008). Ginger.

Navarro, S. (2012). The use of modified and controlled atmospheres for the disinfestation of stored products. *Journal of Pest Science, 85*(3), 301-322. doi:10.1007/s10340-012-0424-3

Park, M., Bae, J., & Lee, D. S. (2008). Antibacterial activity of [10]-gingerol and [12]-gingerol isolated from ginger rhizome against periodontal bacteria. *Phytotherapy Research, 22*(11), 1446-1449. doi:10.1002/ptr.2473

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988a). Compositional changes in ginger rhizomes during storage. *Journal of the American Society for Horticultural Science, 113*(4), 584-588.

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988b). CONTROL OF WEIGHT-LOSS AND SPROUTING OF GINGER RHIZOME IN STORAGE. *HortScience, 23*(4), 734-736.

Pinstrup-Andersen, P. (2009). Food security: definition and measurement. *Food Security, 1*(1), 5-7. doi:10.1007/s12571-008-0002-y

Planella, I., & Myrtle Seepersad, I. P. (1990). *Proceedings of a Workshop on Post Harvest Handling of Horticultural Commodities for Export*: Inter-American Institute for Cooperation on Agriculture.

Plasse, R. (1986). *Vegetable storage, respiration and design criteria in a membrane storage system.* (ML34442 M.Sc.), McGill University (Canada), Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Plotto, A. (2002). Ginger Postharvest Operations. *INPhO compendium*.

Prasad, J., & Vijay, V. K. (2005). Experimental studies on drying of *Zingiber officinale*, Curcuma longa l. and Tinospora cordifolia in solar-biomass hybrid drier. *Renewable Energy, 30*(14), 2097-2109. doi: 10.1016/j.renene.2005.02.007

Pruthi, J. S. (1976). *Spices and condiments*.

Raghavan, G. S. V. (2005). Refrigerated and controlled/modified atmosphere storage. *Processing Fruits, Science and technology*, 23-52.

Raghavan GSV, A. P., Gariepy Y, Vigneault C. (1996). Refrigerated and controlled modified atmosphere storage. *Processing fruits: science and technology*, 135-167.

Raghavan, G. S. V., Gariépy, Y., Thériault, R., et al. (1984). System for controlled atmosphere long-term cabbage storage. *International Journal of Refrigeration, 7*(1), 66-71. doi: 10.1016/0140-7007(84)90057-4

Raghavan, G. S. V., Tessier, S., Chayet, M., et al. (1982). Storage of vegetables in a membrane system. *Transactions of the ASAE, 25*(2), 433-436.

Raghavan, G. S. V. (2005). Refrigerated and controlled/modified atmosphere storage. *Processing Fruits, Science and technology*, 23-52.

Ratti, C., Raghavan, G. S. V., & Gariépy, Y. (1996). Respiration rate model and modified atmosphere packaging of fresh cauliflower. *Journal of Food Engineering, 28*(3), 297-306. doi: 10.1016/0260-8774(95)00044-5

Ravindra, N., Ambrose, D. C. P., Raghavan, G. S. V., et al. (2007). Role of silicone membrane storage on increased shelf life of minimally processed multiplier onion. *Proceedings of the International Agricultural Engineering Conference, Bangkok, Thailand*.

Ravindra, N., & Kailappan, R. (2007). Role of silicone membrane in increasing the shelf-life and quality of tomatoes during storage. *Journal of Food Science and Technology, 44*(3), 301-306.

Rhim, J. W. (2007). Potential use of biopolymer-based nanocomposite films in food packaging applications. *Food Science and Biotechnology, 16*(5), 691-709.

Riad, G. (2004). Atmosphere modification to control quality deterioration during storage of fresh sweetcorn cobs and fresh-cut kernels. (3146245 Ph.D.), University of Florida, Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Sabogal-Guáqueta, A. M., Osorio, E., & Cardona-Gómez, G. P. (2016). Linalool reverses neuropathological and behavioral impairments in old triple transgenic Alzheimer's mice. *Neuropharmacology, 102*, 111-120. doi: 10.1016/j.neuropharm.2015.11.002

Sabulal, B., Dan, M., J, A. J., Kurup, R., et al. (2006). Caryophyllene-rich rhizome oil of *Zingiber nimmonii* from South India: Chemical characterization and antimicrobial activity. *Phytochemistry, 67*(22), 2469-2473. doi: 10.1016/j.phytochem.2006.08.003

Saltveit, M. E. (2004). Respiratory metabolism. *The commercial storage of fruits, vegetables, and florist and nursery stocks. Agriculture Handbook, 66*.

Shaista, J. K. J. J. K. (2010). Effect of different stabilizers on the antibacterial activity of "ginger garlic paste". *J.Appl. Sci. Environ. Manag., 13*, 103-109.

Shchipunov, Y. (2012). Bionanocomposites: Green sustainable materials for the near future. *Pure and Applied Chemistry, 84*(12), 2579-2607. doi:10.1351/PAC-CON-12-05-04

Shukla, Y., & Singh, M. (2007). Cancer preventive properties of ginger: A brief review. *Food and Chemical Toxicology, 45*(5), 683-690. doi: 10.1016/j.fct.2006.11.002

Śledź, M., Nowacka, M., Wiktor, A., et al. (2013). Selected chemical and physico-chemical properties of microwave-convective dried herbs. *Food and Bioproducts Processing, 91*(4), 421-428. doi: 10.1016/j.fbp.2013.02.010

Raghavan, G.S.V., Vigneault, C., Gariépy, Y., et al. (1996). Refrigerated and Controlled/Modified Atmosphere Storage. In *Processing Fruits: Science and Technology*: 2nd edition Taylor & Francis.

Standards, B. B. O. I. (2008). Ginger, whole and ground—specification *Spices and condiments*. Spices and Condiments Sectional Committee, New Delhi.

StatsCanada. (2013). 091011 Ginger, neither crushed nor ground.

Stewart, O. J., Raghavan, G. S. V., Golden, K. D., et al. (2005). MA storage of Cavendish bananas using silicone membrane and diffusion channel systems. *Postharvest Biology and Technology, 35*(3), 309-317. doi:10.1016/j.postharvbio.2004.10.003

Stewart, O. J., Raghavan, G. S. V., Golden, K. D., et al. (2005). MA storage of Cavendish bananas using silicone membrane and diffusion channel systems. *Postharvest Biology and Technology, 35*(3), 309-317. doi: 10.1016/j.postharvbio.2004.10.003

Sultana, S., & Ali, M. (2015). Chemical composition of volatile oil of the rhizome of *Zingiber officinale* roscoe and its antimicrobial activity. *World j. of pharmacy and pharmaceutical sci, 4*, 741-752.

Sutarno, H., Hadad, E.A., and Brink, M. (1999). *Plant resources of South-East Asia, No.13. Spices*. Leiden: Backhuys Publishers.

Thompson, A. (1971). Storage of mango fruits. *Tropical Agriculture, 48*(1), 63-&.

Touba, E. P., Zakaria, M., & Tahereh, E. (2012). Anti-fungal activity of cold and hot water extracts of spices against fungal pathogens of Roselle (Hibiscus sabdariffa) in vitro. *Microbial Pathogenesis, 52*(2), 125-129. doi: 10.1016/j.micpath.2011.11.001

Unni, L. E., Chauhan, O. P., & Raju, P. S. (2015). Quality changes in high pressure processed ginger paste under refrigerated storage. *Food Bioscience, 10*, 18-25. doi: 10.1016/j.fbio.2014.12.005

Varrò, M. T. (1800). The Three Books of M. Torentina Varro Concerning Agriculture, T. Owens (trans.): The University Press, Oxford.

Vigneault, C., Canada, Agriculture, & Agri-Food, C. (1994). *Techniques for controlled atmosphere storage of fruits and vegetables*. [Ottawa]: Research Branch, Agriculture and Agri-Food Canada.

Vijendra Kumar, N., Murthy, P. S., Manjunatha, J. R., & Bettadaiah, B. K. (2014). Synthesis and quorum sensing inhibitory activity of key phenolic compounds of ginger and their derivatives. *Food Chemistry, 159*, 451-457. doi: 10.1016/j.foodchem.2014.03.039

Wang, Y. S., Tian, S. P., & Xu, Y. (2005). Effects of high oxygen concentration on pro- and anti-oxidant enzymes in peach fruits during postharvest periods. *Food Chemistry, 91*(1), 99-104. doi:10.1016/j.foodchem.2004.05.053

Wangcharoen, W. (2012). Development of ginger-flavoured soya milk ice cream: Comparison of data analysis methods. *Maejo International Journal of Science and Technology, 6*(3), 505-513.

Weiss, E. A. (2002). *Spice crops*: CABI.

Wills, R. H. H., Lee, T. H., Graham, D., et al. (1981). *Postharvest. An introduction to the physiology and handling of fruit and vegetables*.

Wolf, B. (2016). Confectionery and Sugar-Based Foods *Reference Module in Food Science*: Elsevier.

Yusof, N. (1990). Sprout inhibition by gamma-irradiation in fresh ginger (Z*ingiber-officinale roscoe*). *Journal of Food Processing and Preservation, 14*(2), 113-122. doi:10.1111/j.1745-4549.1990.tb00833.x

CONNECTING TEXT

In the following chapter, investigations on the modified atmosphere storage of ginger using silicone-membrane based storage system at ambient temperature conditions is described. The silicone-based membranes viz. MSM, CSM, and GC used for this study were selected earlier. The response surface methodology was applied to design the experiments and analyse the various responses of the stored ginger towards each factors investigated.

CHAPTER IV

STORAGE LIFE ENHANCEMENT OF GINGER USING SILICONE MEMBRANE SYSTEM UNDER AMBIENT TEMPERATURE STORAGE CONDITIONS

Priyanka Kamat*, Yvan Gariépy, Jiby Kurian, Vijaya Raghavan

*Corresponding author:

Priyanka Kamat, Department of Bioresource Engineering, McGill University, QC, H9X 3V9, Canada.

Phone: +1-(438)-888-1814, Email: priyanka.kamat@mail.mcgill.ca

Abstract

Ginger is an important spice cash crop that is gaining increasing importance in research and trade across the world. The ginger rhizome has been cultivated over several centuries in the Asian countries, but now it is grown all over the world. Long term postharvest storage of ginger has not been studied in detail by using modified atmosphere storage concept. This study details the use of silicone-based membrane systems in the storage of ginger using response surface methodology for designing the experiment. The stored ginger was analysed on the basis of its firmness, change in stored mass, color change, total phenolic content, and change in gas concentration in the storage chamber.

Keywords: ginger, postharvest, storage, silicone membrane, modified atmosphere, response surface design

4.1 Introduction

Ginger is one of the essential spices in the world, prevalently grown in Asian countries with tropical and sub-tropical climate. The ginger rhizome (*Zingiber officinale*) grows underground, is irregular shaped, branched or palmate and is often used as a spice in cooking or is pickled (Britannica, 2016; Gross et al., 2014). Ancient Chinese and Indian medicine advocates the use of ginger for various ailments including stomach aches, nausea, diarrhea, and as dietary supplements for cold and flu, and as digestives (Kaur et al., 2015; National Center for Complementary & Alternative Medicine, 2008). Various scientific studies have explained the effect of ginger in the treatment of breast cancer, pancreatic cancer, liver cancer, and urinary bladder cancer (Baliga et al., 2011; Shukla et al., 2007). Use of ginger extracts and essential oils has been researched in treating arthritis (Funk et al. 2016), and high-fat-diet-induced obesity in mice (Misawa et al., 2015). Ginger (Fig. 25) is believed to have originated in the Southeast Asia where it was first grown and due to ease of transportation, its use has spread worldwide.

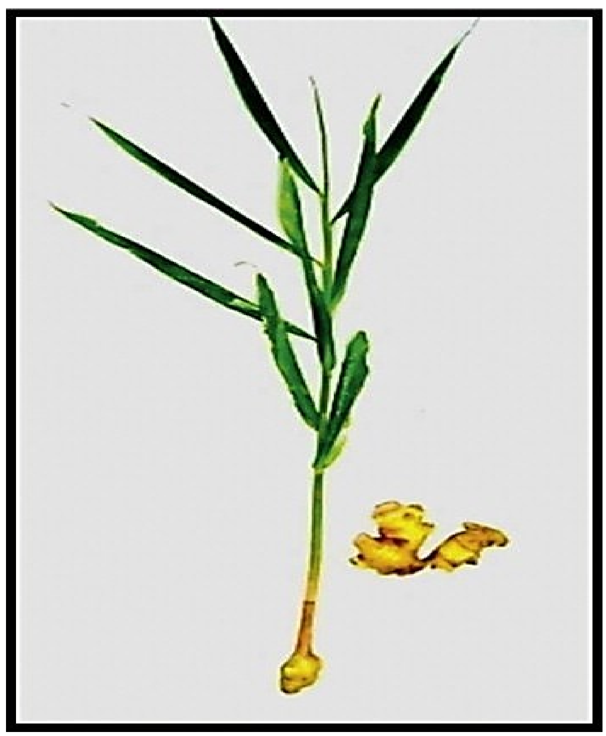

*Fig. 25: Ginger (Zingiber officinale Roscoe) plant and rhizome (Baliga et al., 2013)**

* Reprinted from Critical Reviews in Food Science and Nutrition, *51(6),* Baliga et al., Update on the Chemopreventive Effects of Ginger and its Phytochemicals, 499-423, (2011), with permission from Baliga M. S. (Taylor and Francis publishers).

- **Economic and social impact:**

Ginger has been grown as a spice crop and the production has been steadily increasing over the recent years (Fig. 26). Though India and China remain as the leading producers of ginger in the world, countries like U.S.A. have come up with higher annual yield in the last ten years.

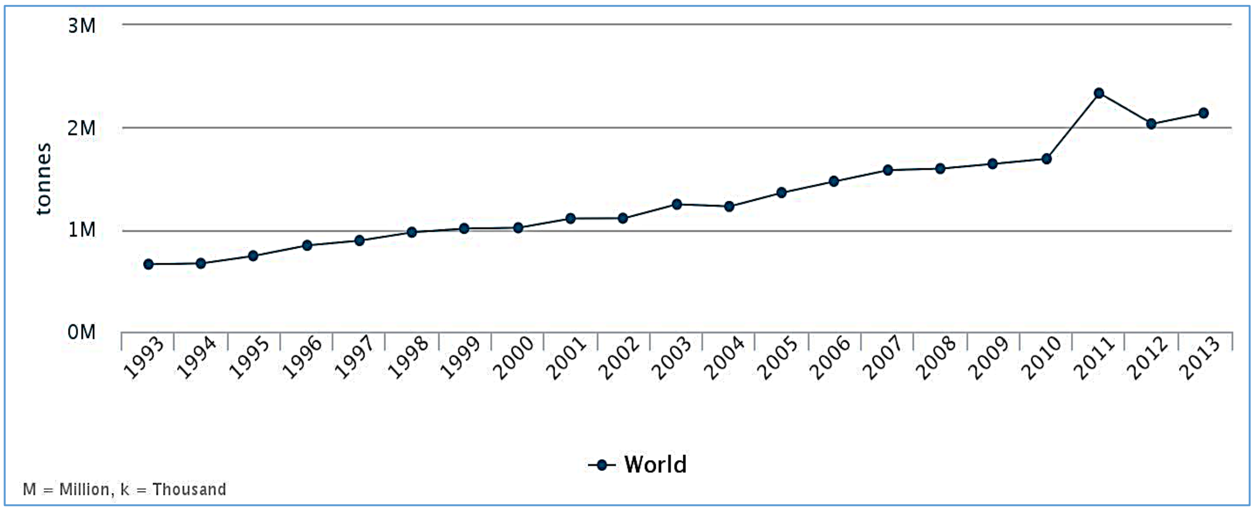

Fig. 26: World production of ginger (1993-2013) (Food & Agriculture Organization of the United, 2014)

Data on the ginger production between 1991-2013 suggests that India has an average yearly ginger production of 343,827 tonnes, followed by China which produces 274,590.66 tonnes, Nepal which produces 129,409.38 tonnes, Thailand produces 128,653.38 tonnes, and Nigeria with 126,026.33 tonnes, making these countries the top five ginger producers in the world (FAO,2014).

4.1.1 Ginger storage

Traditionally, the ginger rhizome is harvested, then washed, peeled and dried before storage. Dried ginger can be stored under ambient conditions for a period of one year, without any noticable change in its antioxidant activity (Nair, 2013). Fresh ginger, however, can only be stored upto 3 months when stored between 12 to 14 °C (Paull et al., 2014). Factors like temperature and relative humidity affect the quality of the stored ginger rhizome.

A well ventilated chamber is used for the storage of ginger. A temperature lower than 10 °C could cause chilling injuries in the stored ginger (Wang et al., 2015). A temperature higher than the optimum storage temperature causes accelerated germination, leading to rotting and decay of the stored ginger.

Proper ventilation in the storage chamber is neccesary to remove the heat produced by the ginger rhizome during the initial stoarge period (Wang et al., 2015). Relative humidity needs to be maintained in the range 85-90 % for the long term storage of ginger. A lower relative humidity may lead to dehydration and wiliting of the stored ginger rhizome (Paull et al., 2014).

Treatments like gamma irradiation of the ginger rhizome before storage has shown to reduce sprouting in the ginger rhizome condierably (Yusof, 1990 ;Mukherjee, 1995). However, the effect of the change in ambient pressure during storage of ginger has not been studied.

4.1.2 Modified atmosphere storage

The factors which are key in the modified atmosphere storage system are the temperature of storage, pressure, relative humidity, and the concentration of atmospheric gases. Other factors include the type of fruit/vegetable stored, the species/cultivar of the stored produce, respiration rate, and the age of stored produce. Membrane-based control systems utilise a silicone membrane which is selectively permeable to certain gases and thus helping in maintaining the modified atmosphere inside the storage container.

Generally, stored ginger with almost no change in extrinsic appearance is preferred. This chief quality criteria is dependent on the level of infestation, freedom from toxic chemicals, and microbial count (Govindarajan, 1982). When it comes to ginger, darkening and rotting of tips is a serious storage issue. Also, the marketability of the ginger depends on its sensory properties.

4.1.3 Response surface methodology for design of experiment

The experiments in this study were conducted by followingthe response surface methodology (RSM) which was developed by Box and Wilson in 1951 (Box et al., 1951). The

RSM develops a second-degree polynomial model in order to find an optimum the conditions for a desired effect. RSM is a statistical design that helps in reducing the number of experiments to be performed when multiple responses need to be studied for two or more factors. Using the RSM, the interaction between the factors and the various responses can be studied. Also, the RSM is useful in experiments where the individual factors are dependent on each other.

4.2 Objectives

The objectives of this study are:

1) To investigate the storage of ginger rhizome using silicone-membrane systems under modified atmosphere and ambient temperature conditions.

2) To determine the effect of storage under modified atmosphere on the firmness, total phenolic content, and the appearance of ginger.

4.3 Materials and Methods

Ginger for storage studies was bought from a local supermarket in Montreal, Quebec, Canada. The obtained ginger was washed and cleaned to remove dirt and superficial impurities.

Three silicone-based membranes, coded as CSM, MSM, and GC were used for the storage studies. The CSM was obtained from China, MSM from Atmolysair, France, and GC from Georgonne Plasticos, Canada. The properties of these membranes were studied and described in Chapter 3. These membranes were selected on the basis of their gas permeability, selectivity ratios, and mechanical strength.

The quality of ginger rhizome was assessed by measuring its physiological properties before and after storage. These properties facilitated to quantify the quality of the stored product. Quantification of gas changes inside the chambers was carried out during the entire storage period at fixed intervals using gas chromatography.

4.4 Equipment and Apparatus

The storage chambers were glass mason jars (1 L) fitted with a lid with two orifices. The first orifice was smaller and was fitted with a septum sealed with silicone glue. This was used for gas sampling from inside the storage container using a syringe, while maintaining its airtightness. The second orifice was a window with a much larger area with the selected silicone-based membrane attached. The area of the membrane was calculated based on the permeability of the membrane attached and the weight of the stored ginger. The procedure to calculate the area was dependant on the desired oxygen concentration inside the chamber. The Fig. 27 provides a schematic of the silicone-membrane based storage system was used for this study.

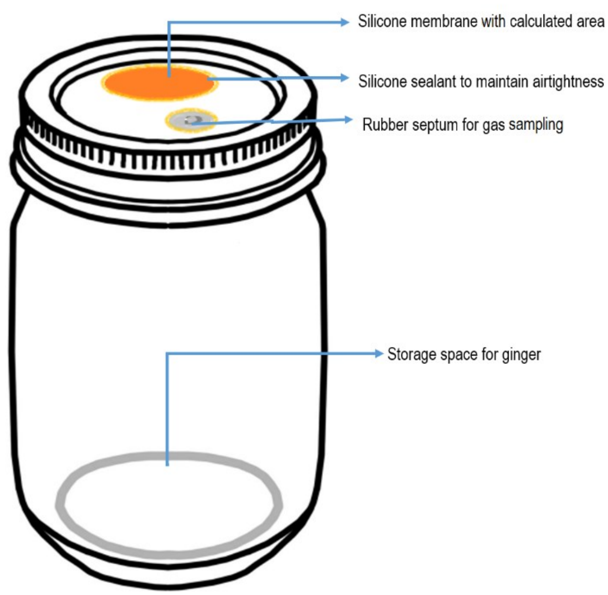

Fig. 27: Mason jar with modifications used for storage of ginger during the experiment

Gas samples were collected at an interval of 1-2 days for the entire duration of storage, and the concentration of CO_2, N_2, and O_2 gases were analysed. The SRI 8610A gas chromatograph with an electronic integrator (SRI Instruments, California, USA) fitted with a thermal conductivity detector (TCD) was used for the gas analysis. A gas sample of 0.25 mL was injected into the instrument and the oven temperature was set at 45 °C with the detector temperature set to 110 °C.

4.5 Experimental Design and Procedure

Response surface design was followed for the experiment. The central composite design (CCD) was used for experimental design in the RSM. The face centred composite (CCF) design was selected with an alpha value of one. An alpha valus of one signifies that the axial points are at the centre of each face of the factorial space.

The design of experiment was prepared using Design-Expert 9.0.6 (Stat-Ease Inc., USA), and the factors and their levels are shown in Table 11. Duration of the storage was 7, 14, and 21 days. The desired oxygen concentrations after storage time, were 2%, 6%, and 10%. Face centred central composite design (CCF) with two numerical factors (namely storage duration and desired oxygen concentration) and one categorical factor at three levels (MSM, CSM, and GC) was designed using the software. The treatments at the axial points were replicated three times and the treatments at central points (storage duration: 14 days and desired oxygen concentration: 6%) were replicated five times.

Table 10: Response Surface Design with the selected parameters

Factor	Level	Description
Desired Oxygen level	1	2%
	2	6%
	3	10%
Storage Duration	1	7 days
	2	14 days
	3	21days
Membrane type	1	MSM
	2	CSM
	3	GC

The experiment was carried out in two stages. The first involved the study of the characteristics of the silicone-based membranes and determining their permeability for the gases. This phase has been discussed in Chapter 3 in detail. The second stage involved the storage of ginger at room temperature and pressure under the atmosphere modified using the silicone membrane system. The ginger was stored in glass mason jars (1 L). The selected silicone-based membrane was cemented to the septum of the lid using silicone based sealant. In order to fit into the storage container, the ginger had to be cut to convenient and workable sizes. This was done using a sharp and clean steel blade.

Since the area of the silicone-based membrane to be placed on the window varied based on the permeability of each membrane and the mass of ginger stored inside the storage container, the desired oxygen concentration was used to mention the area of the membrane in the experiment design for ease and better comprehension.

4.6 Calculation of membrane area and Storage conditions

The areas of the silicone membranes to be used for the storage of ginger were calculated using Equations (9-10). The area of the membrane was dependent on the desired concentration of carbon dioxide or oxygen required at the end of storage period in the storage chamber.

Area of silicone membrane for desired CO_2 concentration:

$$A = \frac{RR_{CO_2} \cdot m}{K_{CO_2} \cdot pp_{CO_2}} \tag{9}$$

Area of silicone membrane for desired O_2 concentration:

$$A = \frac{RR_{O_2} \cdot m}{K_{O_2} \cdot pp_{O_2}} \tag{10}$$

Where, A = membrane area of silicone membrane (m^2)

RR_{CO2} = respiration rate based on CO_2 (l/kg day)

RR_{O2} = respiration rate based on O_2 (l/kg · day)

m = mass of product stored (kg)

K_{CO2} = permeability of membrane to CO_2 (l/ day · m^2 · atm)

K_{O2} = permeability of membrane to O_2 (l/ day · m^2 · atm)

pp_{CO2} = partial pressure across membrane for CO_2 (atm)

pp_{O2} = partial pressure across membrane for O_2 (atm)

The areas (Table 12) of the membrane to be placed on the orifice on the lid were determined by assuming that 20-25% volume (200–250 g) was occupied by ginger. The external atmospheric conditions were monitored and was constant throughout the period of storage. The temperature of the room was set at 23 °C, pressure at one atmosphere, and the relative humidity was maintained at 85 % during the storage period. The ginger once sealed inside the container was only opened when the duration of storage was completed.

The respiration rate of ginger, 5.5 to 6.8 mg CO_2 kg^{-1} h^{-1}, provided in the USDA Handbook was used in the calculations (Paull et al., 2014) of this study. The average of this value was taken and converted to mL CO_2 kg^{-1} h^{-1} by dividing using 1.8 to get 3.05 mL CO_2 kg^{-1} h^{-1}. The partial pressure difference between the membrane and its ambient environment was taken as 0.004 atm.

Table 11: Calculated membrane area values for storage chambers

Type of silicone-based membrane	Measured permeability (L day^{-1} m^{-2} atm^{-1})	Membrane area for 2% desired O2 conc. (m^2)	Membrane area for 6% desired O2 conc. (m^2)	Membrane area 10% desired O2 conc. (m^2)
MSM	1577.6	0.00035	0.00045	0.00061
CSM	3332.2	0.000071	0.000090	0.000123
GC	825.87	0.00035	0.00044	0.00060

4.7 Quality analysis

4.7.1 Percent mass loss

The total mass loss of the stored ginger was calculated by weighing the ginger before storage and after storage in the chamber. Cumulative mass loss on wet basis was derived as percentage mass loss. The mass of ginger stored in the containers with the MSM membrane was around 200 g and the ginger stored in the CSM and GC systems were 250 g in each of the containers.

The Equation (11) was used to calculate the mass loss:

$$Cumulative\ mass\ loss = \frac{Mi - Mf}{Mf} \times 100 \tag{11}$$

Where,

M_i = initial mass of stored ginger at day zero

M_f = final mass of stored ginger after storage period

The mass loss in such storage conditions can only be attributed to the respiration and transpiration (i.e. water loss from the stored product) processes (Yusof, 1990).

4.7.2 Appearance

Change in appearance of ginger was tracked before storage and after storage. Any bruising, mould growth was noted.

Analytical-descriptive checks were performed to assess the sensory quality of ginger before and after storage. Parameters and rating system (Table 13 and Table 14) had to be prepared based on various research articles (Govindarajan, 1982; Kader et al., 1973; Liplap et al., 2014; Ratti et al., 1996). The ginger was scored on factors such as the general appearance, decay or visible mould growth, and fiber growth and budding.

Table 12: Rating scale for general visual appearance

Score	Description
1	Extremely poor, not usable
3	Poor quality, appearance, and the limited marketability
5	Fair; some objectionable defects and lower limit marketability
7	Good; minor defects with good marketability
9	Excellent; principally free of defects

Table 13: Rating scale for visible microbial damage

Score	Description
1	Decayed product, not usable
3	Mould growth covering more than half of stored ginger
5	Visible microbial infestation
7	Minor microbial damage, easily treatable
9	Free of any mould growth

4.7.3 Color

Color analysis is an important aspect of the quality evaluation. Customers tend to select produce based on preconceived ideas of how the product should look, sellers often try to enhance the color properties for better marketability. Color of ginger depends on the cultivar and location of production. The ginger procured for this study had a yellowish color with sheen.

The CIE-Lab color space is more commonly used and applied for the color measurements and hence all measurements were made using this color space. Minolta Chroma Meter, Model # CR-300b (Minolta Inc., Canada) with the Commission Internationale de l'Eclairage's (CIE) L*, a*, and b* color space coordinates (Fig. 28) was used for the color measurements. The L co-ordinate measure the lightness/clarity of a material and the value ranges within 0 (for black) to 100 (for perfectly white) as the maximum. The negative values on a* scale signify the greenness and positive values for redness of the material. The b* scale has negative values for the blue color and positive values for yellow colour of the material (Forero, 2007; McGuire, 1992). Chroma meter was first calibrated using a white standard tile provided by the manufacturer. Measurements were done in duplicates at three different positions on the ginger and the average of the values were used for further calculations.

4.7.4 Total phenolic content (TPC)

TPC of ginger was determined using the Folin–Ciocalteu assay method developed by Singleton, Orthofer, and Lamuela - Raventos (1999). A modified protocol of the assay was used for analysis of the total phenolic content in ginger (Śledź, M. N., Małgorzata, W., Artur,Witrowa-Rajchert, D., 2013; Unni, Chauhan, & Raju, 2015). In this method, the ginger sample (10 g) was pulverised using a high-speed grinder, the obtained product was diluted with 50 mL distilled water. This slurry was filtered and 5.0 mL of the diluted sample was taken in a test tube followed by the addition of 0.5 mL of Folin–Ciocalteu phenol reagent. After 6 min, 5.0 mL of sodium carbonate (7.5% g/mL) solution was added to the mixture. The absorbance of the mixture, after 90 min of reaction in darkness, was measured at 750 nm using a spectrophotometer (UV-726, Shimadzu, Shanghai, China). One mL of 80 % (mL/mL) aqueous methanol was taken as blank. A standard calibration curve was also produced using gallic acid as the reference phenolic compound. The amount of total phenolic content was expressed as gallic acid equivalents (GAE, mg/g of dry sample).

4.7.5 Respiration rate

When fresh fruits or vegetables are stored in an enclosed space, the level of oxygen in the container goes down with a steady increase in carbon dioxide, due to their respiration process (Beaudry, 1999). It has been widely accepted that storing of the fresh fruits or vegetables at an increased level of CO_2 in controlled/modified atmosphere storage, results in slowed respiration rate (Bodbodak et al., 2016; Kader et al., 1989). Reduction in respiration rate signifies a decreased metabolic activity, slower senescence, and hence a longer storage period for the stored product.

Respiration rate is dependent on a number of factors including, the permeability of the silicone membrane, the mass of stored product, the free volume in the storage chamber, and the partial pressure difference across the membrane. A general equation describing respiration rate was put forth by Kirkland et al. (Kirkland et al., 2008) as shown in Equation (12).

$$ro2 = W \cdot f(T, pO2, pCO2) \tag{12}$$

Where,

W= mass of the produce,
T = temperature,
p_{O2} and p_{CO2}= partial pressures of oxygen and carbon dioxide in the immediate atmosphere
f (T, p_{O2}, p_{CO2}) gives O_2 used-up per unit mass

The respiratory quotient (RQ) is the ratio of the carbon dioxide produced to the oxygen consumed by the stored product. The RQ values vary between 0.7 to 1.3 for the fruits and vegetables (Kader et al., 1989). It is generally assumed to be one for aerobic respiration since for every mole of hexose, six mole of oxygen molecules are consumed and six mole of carbon dioxide molecules are produced.

4.8 Results and Discussion

4.8.1 Summary of the responses measured

Summary of the common responses observed during the storage of ginger under the modified atmosphere conditions using three silicone-based membrane systems is given in Table 15.

Table 14: Measured values for responses and suggested model

Response	Number of observations	Minimum	Maximum	Mean	Std. Dev.	Fitted Model
Measured O_2 concentration (%)	39	6.75	18.74	12.30	3.32	RCubic
Percent mass change (%)	39	0.27	2.55	1.09	0.55	Linear
Total col difference (ΔE)	39	2.02	16.42	7.03	3.47	Linear

4.8.2 Changes in ginger during the storage

Ginger was also stored under regular atmospheric conditions and the observed changes in appearance and mass are given in Table 15. All measurements were done in triplicate and standard deviation was calculated. The changes in the appearance and mass of ginger samples stored using MSM, CSM and GC are given in Tables 16, 17 and 18 respectively.

Table 15: The average values of the measured parameters during the regular atmosphere storage of ginger

Control (Regular Atmosphere)	7 days	14 days	21 days
Percent mass change (%)	1.096±0.015	8.46±0.023	14.34±0.027
Firmness (N)	36±4	34±3	39±2
Visual appearance	8	5.5	4
Decay and budding	8	6.5	5
Total color difference (ΔE)	3.80±0.56	12.27±0.68	4.94±0.37

L	59.64±1.42	65.07±2.23	61.181±0.7
a*	4.53±1.14	2.26±1.31	2.1245±0.83
b*	11.115±2.42	4.305±1.75	10.834±0.34

Table 16: The average values of the measured parameters during the storage of ginger using the MSM system over a period of 7, 14, and 21 days with desired oxygen conc. at 2%, 6%, and 10%

Parameter	**7 days**			**14 days**			**21 days**		
Desired oxygen conc.	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**
Measured O_2 conc. (%)	7.38	8.28	11.17	8.412	11.87	14.33	7.09	12.42	13.72
Percent mass change (%)	0.46	0.64	0.72	0.87	1.21	1.79	1.27	2.38	2.55
Visual appearance	8	9	8	7	8	7	7	6.5	6
Decay and budding	8	8	7.5	7.5	6	7	6	5	6

Total color difference (ΔE)	2.02	2.72	2.42	3.16	3.27	3.23	6.50	4.79	5.39
L	65.55	66.37	63.73	65.89	64.40	66.06	64.14	66.12	67.48
a*	5.10	5.17	5.10	6.95	6.75	6.57	8.04	6.77	6.83
b*	16.54	14.78	13.16	14.38	17.11	17.14	21.24	19.30	18.97

Table 17: The average values of the measured parameters during the storage of ginger using the CSM system over a period of 7, 14, and 21 days with desired oxygen conc. at 2%, 6%, and 10%

Parameter	7 days			14 days			21 days		
Desired oxygen conc.	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**
Measured oxygen conc. (%)	14.56	11.16	18.65	16.42	13.67	16.51	18.74	18.11	18.31
Percent mass change (%)	0.44	1.19	0.85	1.43	0.89	0.81	0.76	1.36	0.66
Visual appearance	9	8.5	8.5	7	7.5	7	6	5	5
Decay and budding	7.5	8	8	7	6.5	6.5	4.5	4	4
Firmness (N)	28.00	29.33	29.67	36.67	30.73	31.33	28.67	32.67	28.67
Total color difference (ΔE)	4.44	12.07	6.92	10.58	8.60	11.42	7.71	8.96	10.31
L	63.14	52.29	54.33	65.74	58.55	54.23	61.65	58.19	60.56
a*	5.60	5.36	5.91	-1.22	-0.37	0.31	-0.43	0.66	-0.65
b*	11.23	9.95	9.22	6.46	11.03	11.64	8.13	6.62	4.89

Table 18: The average values of the measured parameters during the storage of ginger using the GC silicone membrane system over a period of 7, 14, and 21 days with desired oxygen conc. at 2%, 6%, and 10%

Parameter	**7 days**			**14 days**			**21 days**		
Desired oxygen conc.	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**	**2%**	**6%**	**10%**
Measured O_2 conc. (%)	12.37	10.04	10.98	12.37	10.24	11.44	6.75	10.21	11.55
Percent mass change (%)	0.40	0.53	0.64	0.80	1.13	1.25	1.17	1.64	1.92
Visual appearance	9	9	8	7	7.5	7	7	6.5	6.5
Decay and budding	8.5	8	9	6	6	6.5	6	5.5	6
Firmness (N)	31.00	37.67	33.33	28.00	30.93	32.67	26.00	32.33	37.33
Total color difference (ΔE)	7.32	4.81	4.51	10.08	8.53	11.45	16.43	10.55	4.70
L	82.69	82.11	81.97	69.82	71.95	63.97	78.03	89.95	77.87
a*	6.34	5.86	5.66	0.43	0.01	0.58	0.43	-0.25	1.12
b*	11.78	13.47	13.37	14.49	12.97	18.96	16.83	6.44	14.38

4.8.3 Changes in ginger under the modified atmosphere storage conditions

Fig. 29 shows the change in gas concentration vs. duration of storage when MSM membrane was used. The storage chamber was fitted with 3.5 cm^2 of Marcellin silicone based membrane for 21 days. The CO_2 levels were increased in the first week of storage and the oxygen levels were decreased. After this initial period, the concentrations of both the gases remained constant throughout the remaining period of storage. However, the desired oxygen concentration of 2 % was not achieved. A similar trend was observed in the case of MSM based storage system with the desired oxygen concentration of 6 % and 10 %.

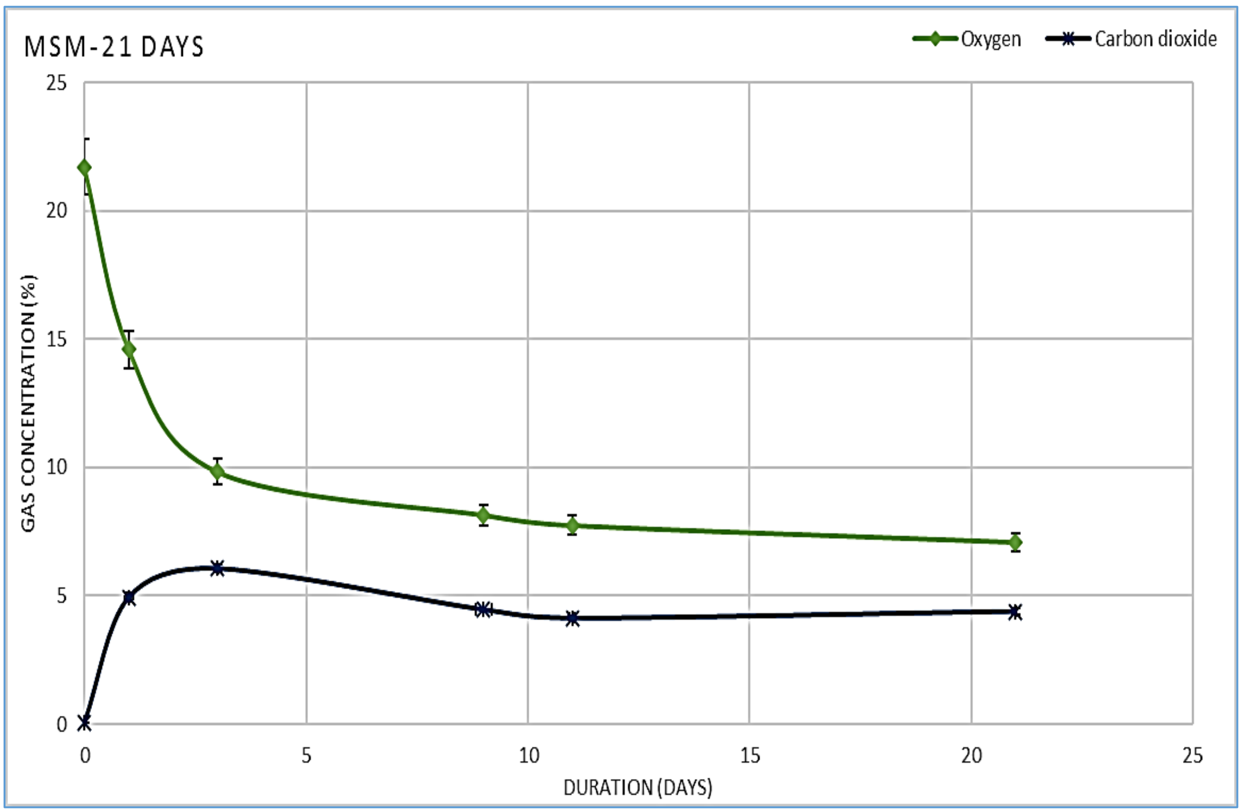

Fig. 28: Carbon dioxide and oxygen concentrations in the MSM system targeted for 2 % oxygen concentration during the 21-day storage of ginger.

Table 19 shows the ANOVA for response surface quadratic model fitted to for the observations of measured oxygen concentration in the storage chamber. The model was significant (F-value at 22.53) and the duration of ginger storage had an effect on the measured oxygen concentration (Table 19).

Table 19: The ANOVA of the measured O_2 concentration during the storage of ginger with the MSM system

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F	Significance
Model	63.60	5	12.72	22.53	0.0004	significant
A-duration	*6.83*	*1*	*6.83*	*12.10*	*0.0103*	
B-oxygen	*44.49*	*1*	*44.49*	*78.78*	*< 0.0001*	
AB	*2.02*	*1*	*2.02*	*3.58*	*0.1003*	
A^2	*6.43*	*1*	*6.43*	*11.38*	*0.0119*	
B^2	*0.71*	*1*	*0.71*	*1.26*	*0.2985*	
Residual	3.95	7	0.56			
Lack of Fit	*3.20*	*3*	*1.07*	*5.68*	*0.0633*	*not significant*
Pure Error	*0.75*	*4*	*0.19*			
Corrected Total	67.55	12				

Fig. 30 shows the change in respiratory gas concentration when the CSM system was used for the modified atmosphere storage of ginger. The graph shows the change in the concentration of carbon dioxide and oxygen gases in the ginger storing system with respect to the duration of storage. The storage chamber was fitted with 0.71 cm^2 of the Chinese silicone-based membrane to achieve the desired 2 % oxygen concentration. From the graph, we can observe that initially there was a rise in the CO_2 levels with a decrease in the O_2 levels. The concentrations of both gases were remained constant in the system after a week in the storage of ginger. Though the desired oxygen concentration wasn't achieved in any of the CSM storage systems, a similar trend was seen for the chambers including in those with the expected oxygen concentration were 6 % and 10 %. This may be due to the uneven structure of the CSM membrane, and some fluctuation was observed in the measured concentration of CO_2 gas (Fig. 30).

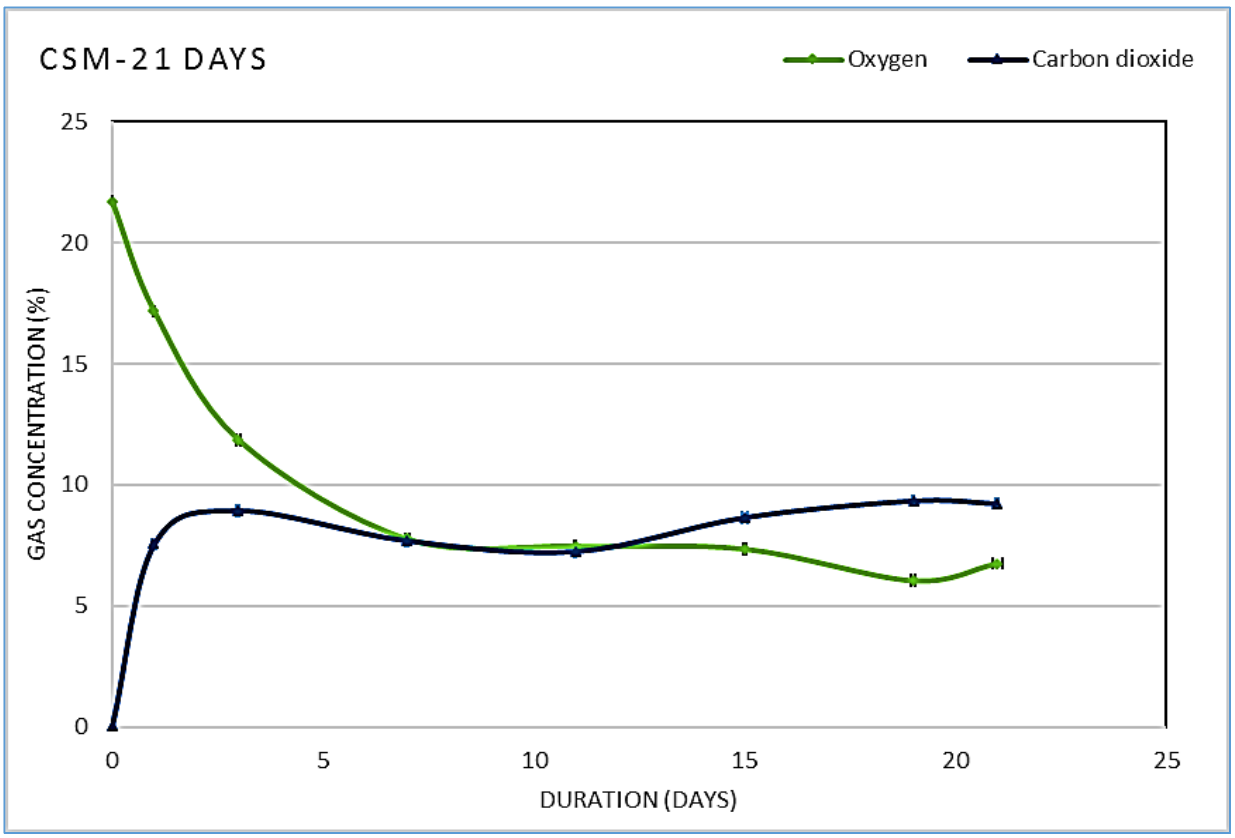

Fig. 29: Carbon dioxide and oxygen concentrations in the CSM system targeted for 2 % oxygen concentration during the 21-day storage of ginger.

The values of the measured oxygen concentration were fitted using a quadratic model but the model was not found to be significant (at $p \leq 0.05$). This implies that, the measured oxygen levels in the modified atmosphere storage of ginger with the CSM membrane were not affected by the duration of storage. The measured oxygen concentrations were much higher than the expected ones.

Table 20: The ANOVA of the measured O_2 concentration during the storage of ginger with the CSM membrane

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	64.07	5	12.81	1.28	0.3700	not significant
A-duration	19.41	1	19.41	1.93	0.2069	
B-oxygen	2.34	1	2.34	0.23	0.6438	
AB	5.12	1	5.12	0.51	0.4982	
A^2	2.94	1	2.94	0.29	0.6050	
B^2	22.64	1	22.64	2.26	0.1767	
Residual	70.24	7	10.03			
Lack of Fit	9.45	3	3.15	0.21	0.8866	not significant
Pure Error	60.79	4	15.20			
Corrected Total	134.31	12				

Fig. 31 shows the change in respiratory gas concentrations when GC membrane was used in the modified atmosphere storage of ginger in a membrane-based system. The change in the concentrations of carbon dioxide and oxygen gases with respect to the ginger storage duration are shown in the figure. The storage chamber was fitted with 3.5 cm^2 of GC silicone-based membrane. The concentration of carbon dioxide gas was increased and oxygen gas concentration was decreased in the first few days of ginger storage. The observed concentrations of CO_2 and O_2 gas were remained constant after a week of the under modified atmosphere storage. The desired oxygen concentration of 2 % wasn't reached and O_2 gas concentration remained high at 5 % to 5.5 %. A similar trend was seen for chambers in which expected oxygen concentration were 6 % and 10 % respectively.

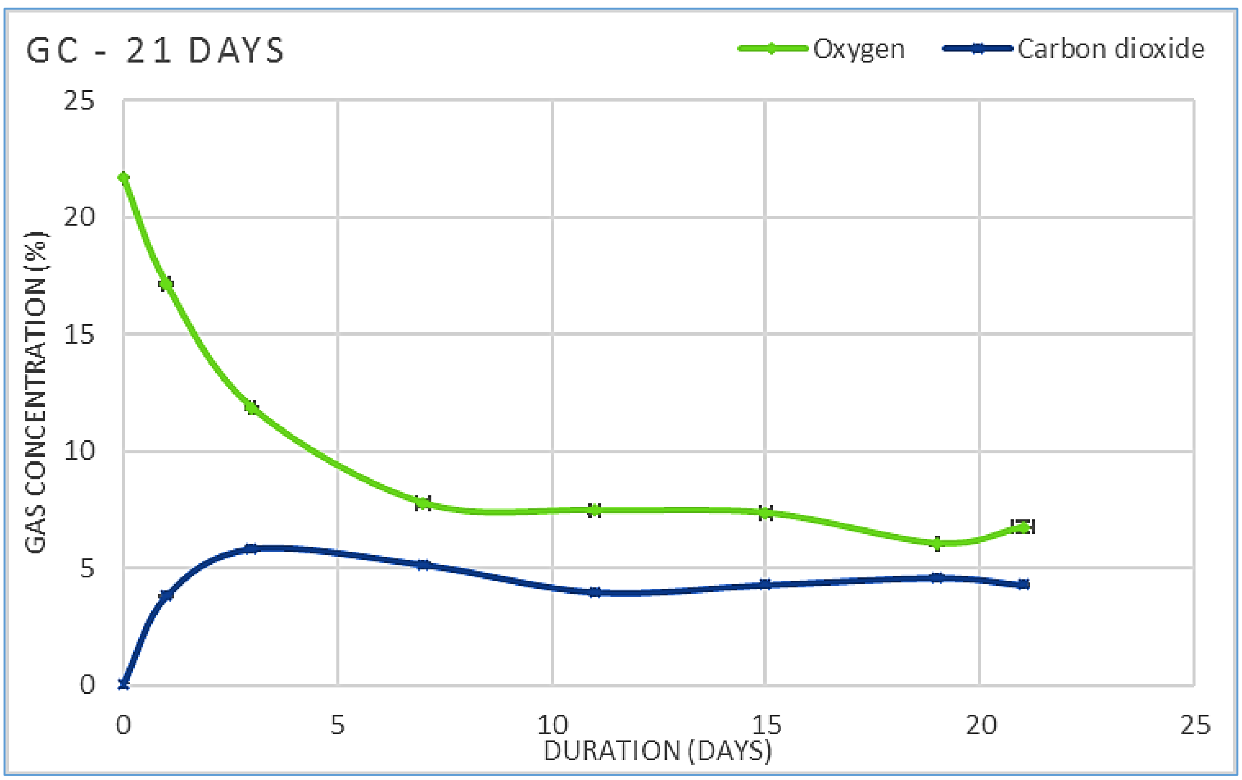

Fig. 30: Change in carbon dioxide and oxygen concentrations during the storage of ginger rhizome using the GC membrane during the 21-day storage period and for 2 % desired oxygen concentration.

.

The ANOVA table for the measured oxygen concentration was fitted to two factor integration (2FI) model (Table 21). An F-value of 4.18 implies the overall significance of the model. However, a significant lack of fit was observed for this model and further improvements in the model is required for the accurate prediction of the O_2 concentration in systems using the GC membrane.

Table 21: The ANOVA of the measured O_2 concentration in the ginger storage systems with GC membrane

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	14.54	3	4.85	4.18	0.0412	significant
A-duration	*3.97*	*1*	*3.97*	*3.43*	*0.0971*	
B-oxygen	*1.02*	*1*	*1.02*	*0.88*	*0.3731*	
AB	*9.55*	*1*	*9.55*	*8.25*	*0.0184*	
Residual	10.43	9	1.16			
Lack of Fit	*9.32*	*5*	*1.86*	*6.70*	*0.0446*	*significant*
Pure Error	*1.11*	*4*	*0.28*			
Corrected Total	24.97	12				

4.8.4 Respiration rate of ginger under the modified atmosphere storage

Ginger rhizome is a non-climacteric crop with low ethylene productivity and can for two to three months at 12-14 °C (Ravindran, 2005). In the experimental setup, ginger was stored in membrane storage system with a gas permeable silicone-membrane window. Due to ginger respiration, the concentration of carbon dioxide in the storage chamber increased gradually, which was desired for the long term storage. The respiration rate of the stored ginger was calculated with respect to carbon dioxide released.

All the three types of silicone-based membranes showed a similar trend for the respiration rate of the stored ginger. Fig. 32, Fig. 33, and Fig 34 show the rapid decrease in the respiration rate of ginger after the first day of storage with a gradual decrease in respiration rate thereafter. A reduced respiration rate was observed throughout the rest of the storage period. A lower respiration rate signifies, slower senescence and metabolic activity, which benefits the long-term storage of fresh produce.

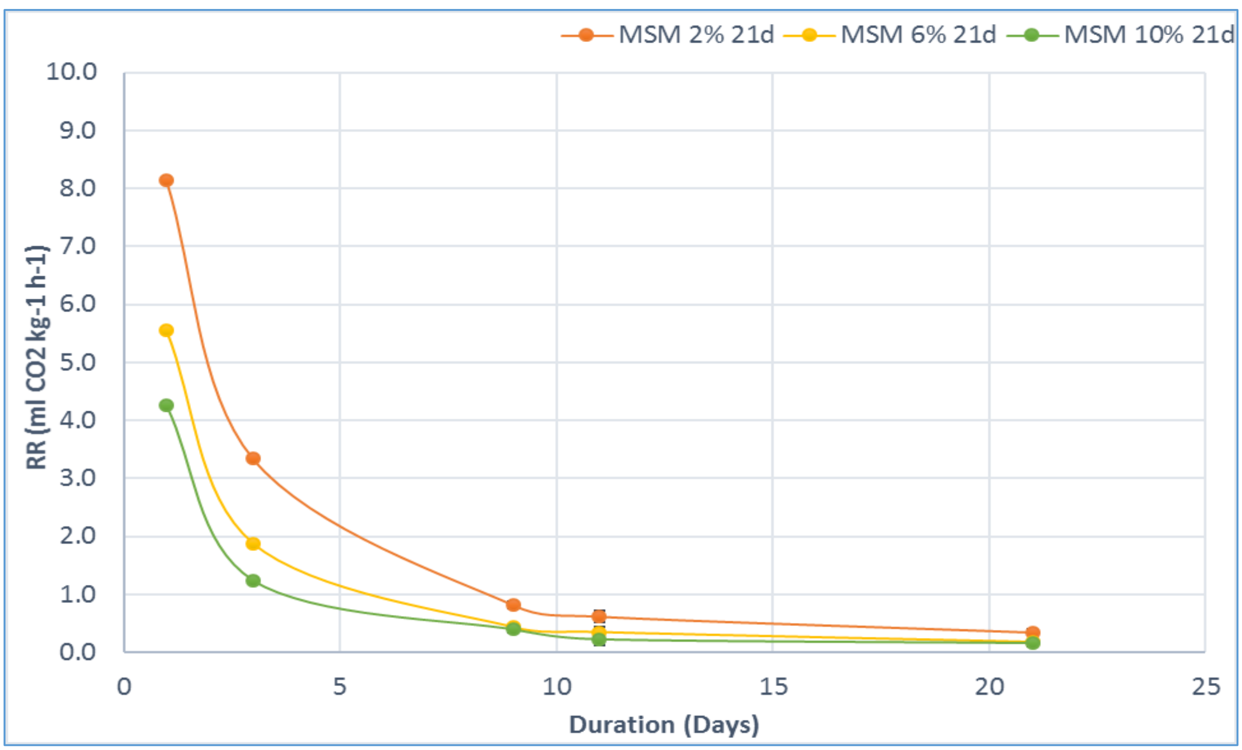

Fig. 31: Respiration rate vs. 21-days duration of storage of ginger under the MSM storage system for the desired oxygen concentration (2%, 6%, 10%)

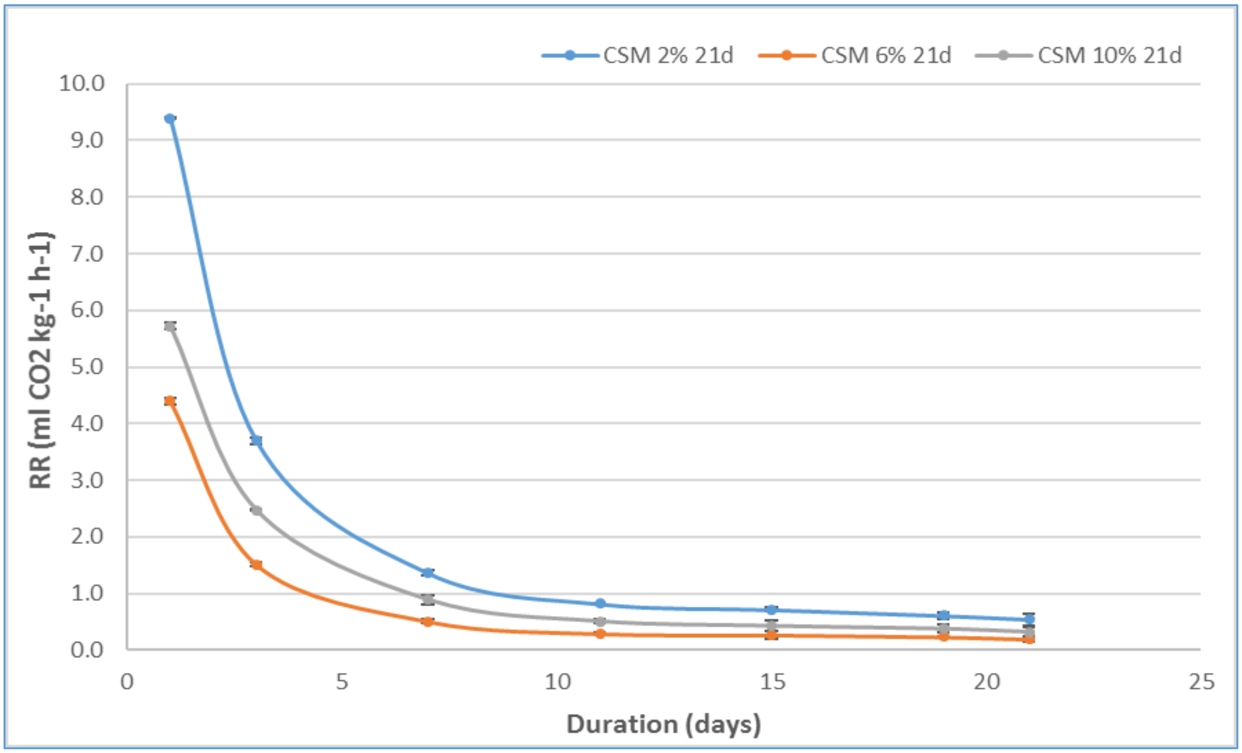

Fig. 32: Respiration rate vs. 14-days duration of storage of ginger under the CSM storage system for desired oxygen concentration (2%, 6%, 10%)

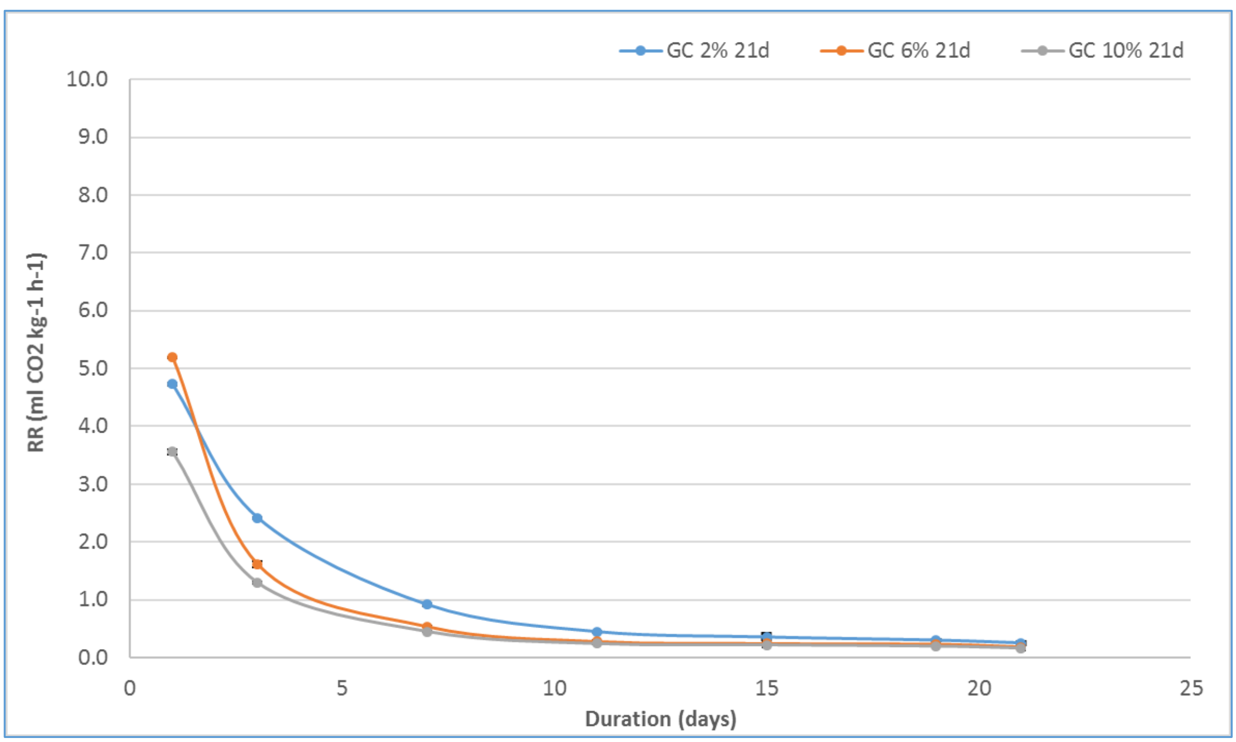

Fig. 33: Respiration rate vs. 21-days duration of storage of ginger under the GC membrane storage system for desired oxygen concentration (2%, 6%, 10%)

Since temperature is one of the factors affecting respiration, a lower temperature would have led to a slower respiration rate. The lowest respiration rate for all three types of membrane systems was observed for the largest membrane area with an expected oxygen concentration of 10%. Higher CO_2 concentration has a partial inhibitory effect on the respiration of the stored produce.

4.8.5 Percent mass loss in the ginger under storage

The percent mass loss was calculated for the ginger stored in membrane-based storage system. For 7 days' storage, the percent mass loss ranged from 0.40 % to 1.19 %. The lower value was observed using GC silicone membrane, while 1.19 % mass loss was observed with the CSM membrane. For 14 days' storage, the percent mass loss ranged from 0.80 %, for ginger stored with the GC membrane, to 1.79 % for the ginger stored with the MSM membrane. The 21-day period, showed a slightly higher percent of mass loss, with 0.66 % for ginger stored with the CSM membrane and 2.55 % as the highest loss observed for the ginger stored with the MSM based system.

Table 22 shows the ANOVA for percent mass loss observed for ginger stored with MSM based system. The duration of storage was found to be significant for the observed percent mass loss while the targeted oxygen concentration was not found to be significant for the measured percent mass loss. The linear model developed was found to be significant ($p \leq 0.05$) with an F-value of 7.20.

Table 22: The ANOVA of the percent mass loss for the ginger stored under the MSM membrane storage system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	4.19	2	2.09	7.20	0.0116	significant
A-duration	*3.18*	*1*	*3.18*	*10.94*	*0.0079*	
B-oxygen	*1.00*	*1*	*1.00*	*3.45*	*0.0929*	
Residual	2.91	10	0.29			
Lack of Fit	*0.46*	*6*	*0.076*	*0.12*	*0.9862*	*not significant*
Pure Error	*2.45*	*4*	*0.61*			
Corrected Total	7.10	12				

Table 23 shows the ANOVA for percent mass loss when the CSM was used for the modified atmosphere storage of ginger. The derived two factor interaction (2FI) model was not found to be significant. The duration of storage and the desired oxygen concentration had no significant effect on the measured percent mass loss.

Table 23: The ANOVA of the percent mass loss of ginger under storage using the CSM membrane

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	0.100	3	0.033	0.21	0.8883	not significant
A-duration	*0.015*	*1*	*0.015*	*0.095*	*0.7648*	
B-oxygen	*0.018*	*1*	*0.018*	*0.11*	*0.7474*	
AB	*0.067*	*1*	*0.067*	*0.42*	*0.5338*	
Residual	1.44	9	0.16			
Lack of Fit	*0.78*	5	*0.16*	*0.95*	*0.5329*	*not significant*
Pure Error	*0.65*	*4*	*0.16*			
Corrected Total	1.54	12				

In table 24, the ANOVA of the mass loss observed for ginger stored under the GC membrane based modified atmosphere storage. The fitted two factor interaction (2FI) model was found to be significant with a high F- value of 67.66. The two factors viz. duration of storage and the desired oxygen concentration were found to be significant when the GC membrane was used for MA storage of ginger.

Table 24: The ANOVA of the percent mass loss of ginger stored under the GC silicone membrane system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	2.07	3	0.69	67.66	< 0.0001	significant
A-duration	*1.67*	*1*	*1.67*	*163.34*	*< 0.0001*	
B-oxygen	*0.34*	*1*	*0.34*	*33.52*	*0.0003*	
AB	*0.062*	*1*	*0.062*	*6.12*	*0.0354*	
Residual	0.092	9	0.010			
Lack of Fit	*0.029*	*5*	*5.864E-003*	*0.38*	*0.8444*	*not significant*
Pure Error	*0.063*	*4*	*0.016*			
Corrected Total	2.16	12				

4.8.6 Visual appearance of the stored ginger

The marketability of any food product depends on its visual appearance. This especially applies to the fresh produces and the perishable goods. The ginger stored under modified atmosphere conditions using the membrane system was evaluated using an analytical-descriptive score, the rubric which is given in Table 12 and Table 13. Table 15, Table 16, Table 17, and Table 18 enlist the scored values for the ginger stored under RA, with MSM, with CSM, and with GC membrane respectively. For ginger, the presence of any rot or microbial damage with budding makes it unmarketable.

The ginger which was stored for 21 days had visible mould growth and budding, hence was considered unmarketable. The budding of ginger is an effect of enzymatic and metabolic activities of the ginger root, or maybe attributed to lower the carbon dioxide concentrations (Mukherjee et al., 1995). Use of irradiation (e.g. gamma rays) can be used to prevent budding in the stored ginger (Yusof, 1990). A lower temperature may also be effective in preventing budding.

4.8.7 Firmness of the stored ginger

High firmness is another desired characteristic of ginger. Since ginger is a fibrous root, heterogeneity exists in its texture which affects the firmness. The firmness was measured in triplicate at three different points on the ginger root after the storage for 7-days, 14-days, and 21-days using MSM, CSM and GC membrane. The firmness of ginger was measured in terms of maximum load (in Newton unit) it could bear. The observed values are listed for the RA, CSM, and GC storage conditions in Table 15, Table 17, and Table 18 respectively. The ANOVA tables for the observed firmness of the ginger samples stored using the CSM and GC membranes were found not to be significant (Table 25 and Table 26). Since the texture of ginger is heterogeneous, firmness of ginger was varied between the samples.

Table 25: The ANOVA of the firmness (maximum load) of the ginger under the CSM storage system

Source	Sum of Squares	df	Mean Square	F -value	p-value Prob >F	Significance
Model	0.45	8	0.057	1.55	0.3546	not significant
A-duration	*0.31*	*1*	*0.31*	*8.41*	*0.0441*	
B-oxygen	*0.12*	*1*	*0.12*	*3.38*	*0.1397*	
AB	*0.19*	*1*	*0.19*	*5.08*	*0.0873*	
A^2	*0.33*	*1*	*0.33*	*9.06*	*0.0395*	
B^2	*0.087*	*1*	*0.087*	*2.36*	*0.1990*	
A^2B	*0.22*	*1*	*0.22*	*5.96*	*0.0711*	
AB^2	*0.14*	*1*	*0.14*	*3.69*	*0.1270*	
A^2B^2	*0.17*	*1*	*0.17*	*4.51*	*0.1009*	
Pure Error	0.15	4	0.037			
Corrected Total	0.60	12				

Table 26: The ANOVA of the firmness (maximum load) of the ginger under the GC silicone membrane storage system

Source	Sum of Squares	df	Mean Square	F- value	p-value Prob > F	Significance
Model	62.70	2	31.35	3.18	0.0852	not significant
A-duration	*6.69*	*1*	*6.69*	*0.68*	*0.4292*	
B-oxygen	*56.02*	*1*	*56.02*	*5.69*	*0.0383*	
Residual	98.49	10	9.85			
Lack of Fit	*58.18*	*6*	*9.70*	*0.96*	*0.5408*	*not significant*
Pure Error	*40.31*	*4*	*10.08*			
Corrected Total	161.20	12				

4.8.8 Color changes in the stored ginger

Fresh ginger had a light yellowish brown appearance. The mean total color difference (ΔE), L, a*, and b* were measured and calculated for the stored ginger. These values of the ginger stored using the MSM, CSM, and GC silicone membrane based storage systems are listed in Table 16, Table 17, and Table 18 respectively.

When the MSM based modified atmosphere storage was applied, the total color difference values were comparatively lower. The ΔE values of the ginger stores for 7 days were ranged from

2.02, for small membrane area, to 2.72 for medium membrane area. Ginger stored for 14-days using the MSM system showed a slightly higher total color difference and was in the range of 3.16 to 3.23. The ginger stored for 21- days with the MSM system showed the highest color difference of 6.50 for the small membrane area. However, the MSM based storage system had the least color difference among the three silicone-based systems used. The L* values (63.73 – 67.48) didn't vary significantly over the storage period. The a* values remained close to the initially measured values. A slight increase was observed in the b* values for ginger stored for 21 days because of the yellowing of the ginger.

Table 28 shows the ANOVA and fitted linear model which was found to be significant for the total color difference in ginger stored using the MSM system. The two factor-interaction (2FI) model for the L* values were not found to be significant (Table 29). The models for the values of a* and b* show a significant fit to the observed values (Table 30 and Table 31). The duration of storage had a significant effect on total color difference (ΔE), L*, a*, and b* values of the stored ginger. The oxygen concentration was not found to be significant for total colour difference (ΔE), L*, a*, b* values of the ginger stored using the MSM system for the modified atmosphere conditions.

When the CSM membrane system was used for the storage of ginger, there was a noticeable increase in the total color difference, with the lowest value of 4.44 for the ginger stored for 7 days with a small membrane, and the highest color difference was seen in ginger stored with the large membrane for 14 days. There was a noticeable change in both the a*, and b* values of the stored ginger. Increase in b* was due to yellowing, negative values for a* were also observed indicating browning (red hues) of the stored ginger.

The total colour difference was not found to be significant when the CSM was used and the data is given in Table 32. The fitted linear model for the L* value of the ginger was found to be significant and the fitted quadratic model for the a* value of ginger was found to be significant (Table 33 and Table 34). The b* value for ginger stored using the CSM did not show any significant fit (at $p \leq 0.05$) (Table 35).

The GC silicone-based membrane ginger storage system lead to a visible increase in the total color difference for the stored ginger. The highest color difference of 16.43 was observed for ginger stored in the small area 21-days storage system.

The linear model for the total colour difference of the stored ginger was found to be significant for the GC membrane storage and is given in Table 36. The fitted quadratic model for the lightness (L*) values and a* values observed were found to be significant (Table 37 and Table 38). The b* values were fitted by a linear model which was found to be not significant (Table 39).

Table 27: The ANOVA for the total color difference in the ginger stored using the three different membranes

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	292.01	4	73.00	14.77	< 0.0001	significant
A-Duration	*52.88*	*1*	*52.88*	*10.69*	*0.0025*	*significant*
B-Oxygen Conc.	*6.38*	*1*	*6.38*	*1.29*	*0.2638*	*not significant*
C-Membrane type	*232.75*	*2*	*116.38*	*23.54*	*< 0.0001*	
Residual	168.10	34	4.94			
Lack of Fit	*125.10*	*22*	*5.69*	*1.59*	*0.2052*	*not significant*
Pure Error	*43.00*	*12*	*3.58*			
Corrected Total	460.11	38				

Table 28 shows the ANOVA of the total color difference of the ginger stored using the three different membrane systems. The model F-value of 14.77 implies the model to be significant. There is only a 0.01% chance that an F-value this large could occur due to noise. In this case, the duration and membrane type had a significant effect on the total color difference, but oxygen concentration was found to be insignificant. The lack of fit values implies the lack of fit is insignificant relative to the pure error.

Table 28: The ANOVA of the total color difference in stored ginger under the MSM membrane storage system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	15.09	2	7.55	10.38	0.0036	significant
A-duration	*15.02*	*1*	*15.02*	*20.66*	*0.0011*	
B-oxygen	*0.070*	*1*	*0.070*	*0.096*	*0.7629*	
Residual	7.27	10	0.73			
Lack of Fit	*3.36*	*6*	*0.56*	*0.57*	*0.7416*	*not significant*
Pure Error	*3.91*	*4*	*0.98*			
Corrected Total	22.37	12				

Table 29: The ANOVA of the lightness (L) in the stored ginger under the MSM membrane storage system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	7.86	3	2.62	1.21	0.3607	not significant
A-duration	*0.72*	*1*	*0.72*	*0.33*	*0.5771*	
B-oxygen	*0.48*	*1*	*0.48*	*0.22*	*0.6493*	
AB	*6.66*	*1*	*6.66*	*3.08*	*0.1134*	
Residual	19.48	9	2.16			
Lack of Fit	*7.34*	*5*	*1.47*	*0.48*	*0.7772*	*not significant*
Pure Error	*12.14*	*4*	*3.04*			
Corrected Total	27.34	12				

Table 30: The ANOVA of the a value of the stored ginger under the MSM membrane storage system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	7.04	2	3.52	12.34	0.0020	significant
A-duration	*6.62*	*1*	*6.62*	*23.21*	*0.0007*	
B-oxygen	*0.42*	*1*	*0.42*	*1.48*	*0.2523*	
Residual	2.85	10	0.29			
Lack of Fit	*1.78*	*6*	*0.30*	*1.11*	*0.4809*	*not significant*
Pure Error	*1.07*	*4*	*0.27*			
Corrected Total	9.90	12				

Table 31: The ANOVA of the b value of the stored ginger under the MSM membrane storage system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	39.15	2	19.58	6.88	0.0132	significant
A-duration	*37.76*	*1*	*37.76*	*13.27*	*0.0045*	
B-oxygen	*1.39*	*1*	*1.39*	*0.49*	*0.5004*	
Residual	28.46	10	2.85			
Lack of Fit	*14.97*	*6*	*2.50*	*0.74*	*0.6474*	*not significant*
Pure Error	*13.49*	*4*	*3.37*			
Corrected Total	67.61	12				

Table 32: The ANOVA of the total color difference in the stored ginger under the CSM membrane storage system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	7.94	2	3.97	0.74	0.5030	not significant
A-duration	*2.10*	*1*	*2.10*	*0.39*	*0.5468*	
B-oxygen	*5.85*	*1*	*5.85*	*1.08*	*0.3223*	
Residual	53.92	10	5.39			
Lack of Fit	*38.98*	*6*	*6.50*	*1.74*	*0.3081*	*not significant*
Pure Error	*14.94*	*4*	*3.74*			
Corrected Total	61.87	12				

Table 33: The ANOVA of the lightness (L) of the stored ginger under the CSM membrane storage system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	95.20	2	47.60	4.81	0.0344	significant
A-duration	*18.83*	*1*	*18.83*	*1.90*	*0.1977*	
B-oxygen	*76.36*	*1*	*76.36*	*7.72*	*0.0195*	
Residual	98.93	10	9.89			
Lack of Fit	*68.54*	*6*	*11.42*	*1.50*	*0.3611*	*not significant*
Pure Error	*30.39*	*4*	*7.60*			
Corrected Total	194.12	12				

Table 34: The ANOVA of the a value of the stored ginger under the CSM membrane storage system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	81.71	5	16.34	32.23	0.0001	significant
A-duration	*49.74*	*1*	*49.74*	*98.10*	*< 0.0001*	
B-oxygen	*0.45*	*1*	*0.45*	*0.88*	*0.3798*	
AB	*0.072*	*1*	*0.072*	*0.14*	*0.7183*	
A^2	*28.42*	*1*	*28.42*	*56.05*	*0.0001*	
B^2	*0.18*	*1*	*0.18*	*0.35*	*0.5744*	
Residual	3.55	7	0.51			
Lack of Fit	*1.64*	*3*	*0.55*	*1.14*	*0.4340*	*not significant*
Pure Error	*1.91*	*4*	*0.48*			
Corrected Total	85.26	12				

Table 35: The ANOVA of the b value of the stored ginger under the CSM membrane storage system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	48.52	5	9.70	0.89	0.5326	not significant
A-duration	*19.31*	*1*	*19.31*	*1.78*	*0.2239*	
B-oxygen	*1.204E-003*	*1*	*1.204E-003*	*1.110E-004*	*0.9919*	
AB	*0.38*	*1*	*0.38*	*0.035*	*0.8572*	
A^2	*12.93*	*1*	*12.93*	*1.19*	*0.3111*	
B^2	*5.36*	*1*	*5.36*	*0.49*	*0.5046*	
Residual	75.94	7	10.85			
Lack of fit	*25.97*	*3*	*8.66*	*0.69*	*0.6026*	*not significant*
Pure error	*49.97*	*4*	*12.49*			
Corrected Total	124.46	12				

Table 36: The ANOVA of the total color difference in the stored ginger under the GC silicone membrane system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	66.52	2	33.26	4.34	0.0439	significant
A-duration	*37.64*	*1*	*37.64*	*4.91*	*0.0510*	
B-oxygen	*28.88*	*1*	*28.88*	*3.77*	*0.0809*	
Residual	76.61	10	7.66			
Lack of Fit	*56.71*	*6*	*9.45*	*1.90*	*0.2783*	*not significant*
Pure Error	*19.90*	*4*	*4.97*			
Corrected Total	143.13	12				

Table 37: The ANOVA of the lightness (L) of the stored ginger under the GC silicone membrane system

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	524.49	5	104.90	7.35	0.0104	significant
A-duration	*0.14*	*1*	*0.14*	*9.780E-003*	*0.9240*	
B-oxygen	*7.53*	*1*	*7.53*	*0.53*	*0.4912*	
AB	*0.080*	*1*	*0.080*	*5.593E-003*	*0.9425*	
A^2	*516.55*	*1*	*516.55*	*36.20*	*0.0005*	
B^2	*82.24*	*1*	*82.24*	*5.76*	*0.0474*	
Residual	99.88	7	14.27			
Lack of Fit	*59.98*	*3*	*19.99*	*2.00*	*0.2557*	*not significant*
Pure Error	*39.89*	*4*	*9.97*			
Corrected Total	624.37	12				

Table 38: The ANOVA of the a value of the stored ginger under the GC silicone membrane system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	76.80	5	15.36	27.61	0.0002	significant
A-duration	*45.71*	*1*	*45.71*	*82.17*	*< 0.0001*	
B-oxygen	*3.750E-003*	*1*	*3.750E-003*	*6.742E-003*	*0.9369*	
AB	*0.47*	*1*	*0.47*	*0.85*	*0.3873*	
A^2	*22.22*	*1*	*22.22*	*39.95*	*0.0004*	
B^2	*0.78*	*1*	*0.78*	*1.40*	*0.2750*	
Residual	3.89	7	0.56			
Lack of Fit	*0.27*	*3*	*0.090*	*0.099*	*0.9566*	*not significant*
Pure Error	*3.63*	*4*	*0.91*			
Corrected Total	80.69	12				

Table 39: The ANOVA of the b value of the stored ginger under the GC silicone membrane system*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	2.33	2	1.17	0.082	0.9217	not significant
A-duration	*0.16*	*1*	*0.16*	*0.011*	*0.9184*	
B-oxygen	*2.18*	*1*	*2.18*	*0.15*	*0.7035*	
Residual	141.98	10	14.20			
Lack of Fit	*94.57*	*6*	*15.76*	*1.33*	*0.4084*	*not significant*
Pure Error	*47.41*	*4*	*11.85*			
Corrected Total	144.31	12				

4.8.9 Total phenolic content

Phenolic compounds in spices are responsible for many of the antioxidant activity (Lu, Yuan, Zeng, & Chen, 2011). These phytochemicals present in ginger mainly free radical scavengers (Embuscado, 2015). The total polyphenolic content was measured in terms of mg gallic acid equivalents (GAE) present per g of sample. The calibration curve was first plotted and the equation:

$$y = 0.0104x + 0.1437 \quad (12)$$

(Where, $R^2 = 0.9877$) was determined where y = absorbance at 750 nm and x = mg GAE L^{-1}. The dilution factor was 25 for the TPC determination. The final total phenolic content was calculated in terms of mg GAE/ g of ginger sample. The total phenolic content was derived for the ginger stored under CSM and GC membrane storage (Table 17, Table 18). Table 40 shows the ANOVA using fitted response surface linear model for the TPC using CSM. The overall model is significant and the duration and observed oxygen concentration also have significant effect on the TPC. The TPC content response surface linear model was not significant for the ginger stored using GC membrane (Table 41).

Table 40: The ANOVA of the TPC of the stored ginger under the CSM membrane

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	213.13	2	106.57	16.65	0.0007	significant
A-duration	*128.03*	*1*	*128.03*	*20.00*	*0.0012*	
B-oxygen	*85.10*	*1*	*85.10*	*13.29*	*0.0045*	
Residual	64.02	10	6.40			
Lack of Fit	*25.72*	*6*	*4.29*	*0.45*	*0.8189*	*not significant*
Pure Error	*38.30*	*4*	*9.58*			
Corrected Total	277.15	12				

Table 41: The ANOVA of the TPC of the stored ginger under the GC silicone membrane

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	79.49	2	39.74	2.07	0.1771	not significant
A-duration	*78.47*	*1*	*78.47*	*4.08*	*0.0709*	
B-oxygen	*1.02*	*1*	*1.02*	*0.053*	*0.8228*	
Residual	192.12	10	19.21			
Lack of Fit	*91.44*	*6*	*15.24*	*0.61*	*0.7227*	*not significant*
Pure Error	*100.68*	*4*	*25.17*			
Corrected Total	271.61	12				

4.9 Conclusions

Three silicone-based membranes, namely MSM, CSM, and GC membrane, were used for the modified atmosphere storage of ginger rhizome at ambient temperature conditions. The measured parameters were statistically analysed and fitted to the mathematical models. The models for the measured responses of the ginger stored using MSM and GC membranes were found to be significant. The models fitted for the responses of the ginger stored under the CSM systems were found to be less significant.

During the ginger storage, the oxygen concentration decreased and the carbon dioxide concentration increased, as observed at regular intervals during the storage period. A decrease in the respiration rate was observed for the ginger rhizome in MA storage.

4.10 Acknowledgements

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Georgonne Plasticos (Quebec, Canada). The author would like to thank Dr. Darwin Lyew for providing insight and expertise, and timely advice that greatly assisted in executing the study.

References

Abd Allah, E. S. H., Makboul, R., & Mohamed, A. O. (2016). Role of serotonin and nuclear factor-kappa B in the ameliorative effect of ginger on acetic acid-induced colitis. *Pathophysiology, 23*(1), 35-42. doi: 10.1016/j.pathophys.2015.12.001

Abdel-Naeem, H. H. S., & Mohamed, H. M. H. (2016). Improving the physico-chemical and sensory characteristics of camel meat burger patties using ginger extract and papain. *Meat Science, 118*, 52-60. doi: 10.1016/j.meatsci.2016.03.021

Afek, U., & Kays, S. J. (2004). Postharvest physiology and storage of widely used root and tuber crops. *Hort Rev, 30*, 253-318.

AGMARK. (2005). Spice Grading and Marking Rules.

Agudo, J. E., Pardo, P. J., Sánchez, H., et al. (2014). A low-cost real color picker based on arduino. *Sensors, 14*(7), 11943-11956.

Akamine, E. K. (1977). Tropical and subtropical crops in Hawaii. *CSIRO Food Research Quarterly, 37*(1), 13-20.

Ali, B. H., Blunden, G., Tanira, M. O., et al. (2008). Some phytochemical, pharmacological and toxicological properties of ginger (Zingiber officinale Roscoe): a review of recent research. *Food Chem Toxicol, 46*(2), 409-420. doi:10.1016/j.fct.2007.09.085

An, K., Zhao, D., Wang, Z., Wu, J., et al. (2016). Comparison of different drying methods on Chinese ginger (Zingiber officinale Roscoe): Changes in volatiles, chemical profile, antioxidant properties, and microstructure. *Food Chemistry, 197, Part B*, 1292-1300. doi: 10.1016/j.foodchem.2015.11.033

Baliga, M. S., Haniadka, R., Pereira, M. M., et al. (2011). Update on the Chemopreventive Effects of Ginger and its Phytochemicals. *Critical Reviews in Food Science and Nutrition, 51*(6), 499-523. doi:10.1080/10408391003698669

Baliga, M. S., Latheef, L., Haniadka, R., et al. (2013). Chapter 41 - Ginger (Zingiber officinale Roscoe) in the Treatment and Prevention of Arthritis A2 - Watson, Ronald Ross. In V. R. Preedy (Ed.), *Bioactive Food as Dietary Interventions for Arthritis and Related Inflammatory Diseases* (pp. 529-544). San Diego: Academic Press.

Bandyopadhyay, M., Chakraborty, R., & Raychaudhuri, U. (2007). A process for preparing a natural antioxidant enriched dairy product (Sandesh). *Lwt-Food Science and Technology, 40*(5), 842-851. doi:10.1016/j.lwt.2006.05.007

Barrett, D. M., Somogyi, L., & Ramaswamy, H. S. (2004). *Processing Fruits: Science and Technology, Second Edition*: CRC Press.

Beaudry, R. M. (1999). Effect of O2 and CO2 partial pressure on selected phenomena affecting fruit and vegetable quality. *Postharvest Biology and Technology, 15*(3), 293-303. doi: 10.1016/S0925-5214(98)00092-1

Bodbodak, S., & Moshfeghifar, M. (2016). 2 - Advances in controlled atmosphere storage of fruits and vegetables A2 - Siddiqui, Mohammed Wasim *Eco-Friendly Technology for Postharvest Produce Quality* (pp. 39-76): Academic Press.

Box, G., & Wilson, K. (1951). On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society. Series B (Methodological), 13*(1), 1-45. Retrieved from http://www.jstor.org/stable/2983966

Britannica, E. (2016). ginger.

Butler, E. J. (1907). An account of the genus Pythium and some Chytridiaceae: Thacker.

Paull, R. E.& Chen, C. C. (2014). *Ginger* USDA (Ed.) *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*

Chong, K. L., Peng, N., Yin, H., et al. (2013). Food sustainability by designing and modelling a membrane controlled atmosphere storage system. *Journal of Food Engineering, 114*(3), 361-374. doi:10.1016/j.jfoodeng.2012.08.027

Chung, H.-S., & Moon, K.-D. (2011). Sprouting and quality control of fresh ginger rhizomes by modified atmosphere packaging with film perforation. *Food Science and Biotechnology, 20*(3), 621-627. doi:10.1007/s10068-011-0088-4

Donohue, M. D., Minhas, B. S., & Lee, S. Y. (1989). Permeation behavior of carbon dioxide-methane mixtures in cellulose acetate membranes. *Journal of Membrane Science, 42*(3), 197-214. doi: 10.1016/S0376-7388(00)82376-5

Embuscado, M. E. (2015). Spices and herbs: Natural sources of antioxidants – a mini review. *Journal of Functional Foods, 18, Part B*, 811-819. doi: 10.1016/j.jff.2015.03.005

Ettouney, H. M., Al-Enezi, G., Hamam, S. E. M., et al. (1994). Characterization of the permeation properties of CO2, N2 gas mixtures in silicone rubber membranes. *Gas Separation & Purification, 8*(1), 31-36. doi:10.1016/0950-4214(94)85005-4

FAO, (2013). The State of Food Insecurity in the World 2013. Multiple Dimensions of Food Security. http://www.fao.org/docrep/018/i3434e/i3434e00.htm [last accessed on 13 July 2016].

Farber, J. N., Harris, L. J., Parish, M. E., et al. (2003). Microbiological Safety of Controlled and Modified Atmosphere Packaging of Fresh and Fresh-Cut Produce. *Comprehensive Reviews in Food Science and Food Safety, 2*, 142-160. doi:10.1111/j.1541-4337.2003.tb00032.x

Figoli, A., De Luca, G., & Drioli, E. (2007). Polymeric capsule production for food packaging application. *ITALIAN JOURNAL OF FOOD SCIENCE, 19*, 90-96.

Finnegan, E., Mahajan, P. V., O'Connell, M., et al. (2013). Modelling respiration in fresh-cut pineapple and prediction of gas permeability needs for optimal modified atmosphere packaging. *Postharvest Biology and Technology, 79*, 47-53. doi: 10.1016/j.postharvbio.2012.12.015

Fonseca, S. C., Oliveira, F. A. R., & Brecht, J. K. (2002). Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: a review. *Journal of Food Engineering, 52*(2), 99-119. doi: 10.1016/S0260-8774(01)00106-6

Food, & Agriculture Organization of the United, N. (2014). FAOSTAT.

Forero, M. P. (2007). Storage life enhancement of avocado fruits. (Master's Dissertation), McGill University.

Funk, J. L., Frye, J. B., Oyarzo, J. N., et al. (2016) Anti-Inflammatory Effects of the Essential Oils of Ginger (Zingiber officinale Roscoe) in Experimental Rheumatoid Arthritis. *PharmaNutrition*. doi: 10.1016/j.phanu.2016.02.004

Gariepy, Y., Munroe, J. A., Raghavan, G. S. V., et al. (1987). Data acquisition and control of storage environment *Paper, American Society of Agricultural Engineers; 1987. (87-4070):23pp. 11 ref.*

Gariepy, Y., & Raghavan, G. S. V. (1989). A mathematical model for a pressure regulated silicone membrane gas permeator for CA storage *Paper - American Society of Agricultural Engineers; 1989. (89-4049):16 pp.*

Gariepy, Y., Raghavan, G. S. V., Castaigne, F., et al. (1991). Precooling and modified atmosphere storage of green asparagus. *Journal of Food Processing and Preservation, 15*(3), 215-224.

Gariépy, Y., Raghavan, G. S. V., & Munroe, J. A. (1994). Long-term storage of leek stalks under regular and controlled atmospheres. *International Journal of Refrigeration, 17*(2), 140-144. doi: 10.1016/0140-7007(94)90056-6

Gariepy, Y., Raghavan, G. S. V., & Theriault, R. (1984). Use of the membrane system for long-term CA storage of cabbage. *Canadian Agricultural Engineering, 26*(2), 105-109.

Gariépy, Y., Raghavan, G. S. V., & Thériault, R. (1986). Controlled atmosphere storage of celery with the silicone membrane system. *International Journal of Refrigeration, 9*(4), 234-239. doi: 10.1016/0140-7007(86)90096-4

Gariepy, Y., Raghavan, G. S. V., Theriault, R., et al. (1988). Design procedure for the silicone membrane system used for controlled atmosphere storage of leeks and celery. *Canadian Agricultural Engineering, 30*(2), 231-236.

Gopala Rao, C. (2015). Chapter 33 - Equipment for Producing and Regulating Controlled Atmosphere. In C. G. Rao (Ed.), *Engineering for Storage of Fruits and Vegetables* (pp. 583-598): Academic Press.

Govindarajan, V. S. (1982). Ginger--chemistry, technology, and quality evaluation: part 1. *Crit Rev Food Sci Nutr, 17*(1), 1-96. doi:10.1080/10408398209527343

Gross, K. C., Wang, C. Y. & Salveit, M.(2014). The commercial storage of fruits, vegetables, and florist and nursery stocks.

Gümüşay, Ö. A., Borazan, A. A., Ercal, N., et al. (2015). Drying effects on the antioxidant properties of tomatoes and ginger. *Food Chemistry, 173*, 156-162. doi: 10.1016/j.foodchem.2014.09.162

Hubert, B., Rosegrant, M., van Boekel, M. A. J. S., et al. (2010). The Future of Food: Scenarios for 2050. *Crop Science, 50*(Supplement_1), S-33-S-50. doi:10.2135/cropsci2009.09.0530

Jacob, J. N. (2016). Chapter 4 - Comparative Studies in Relation to the Structure and Biochemical Properties of the Active Compounds in the Volatile and Nonvolatile Fractions of Turmeric (C. longa) and Ginger (Z. officinale). In R. Atta ur (Ed.), *Studies in Natural Products Chemistry* (Vol. Volume 48, pp. 101-135): Elsevier.

Jakribettu, R. P., Boloor, R., Bhat, H. P., et al. (2016). Chapter 50 - Ginger (Zingiber officinale Rosc.) Oils A2 - Preedy, Victor R *Essential Oils in Food Preservation, Flavor and Safety* (pp. 447-454). San Diego: Academic Press.

Kader, A., Lipton, W. J., & Morris, L. (1973). Systems for scoring quality of harvested lettuce. *HortSci*.

Kader, A. A. (2004). *Increasing food availability by reducing postharvest losses of fresh produce.* Paper presented at the V International Postharvest Symposium 682.

Kader, A. A., Zagory, D., & Kerbel, E. L. (1989). Modified atmosphere packaging of fruits and vegetables. *Crit Rev Food Sci Nutr, 28*(1), 1-30. doi:10.1080/10408398909527506

Kaur, K., Saxena, A., Haniadka, R., et al. (2015). Chapter 6 - Medicinal Benefits of Ginger in Various Gastrointestinal Ailments: Use in Geriatric Conditions A2 - Watson, Ronald Ross *Foods and Dietary Supplements in the Prevention and Treatment of Disease in Older Adults* (pp. 51-61). San Diego: Academic Press.

Kawamoto, Y., Ueno, Y., Nakahashi, E., et al. (2016). Prevention of allergic rhinitis by ginger and the molecular basis of immunosuppression by 6-gingerol through T cell inactivation. *The Journal of Nutritional Biochemistry, 27*, 112-122. doi: 10.1016/j.jnutbio.2015.08.025

Kays, S. J. (1991). *Postharvest physiology and handling of perishable plant products*: Van Nostrand Reinhold Inc.

Kim, D.-H., & Lee, Y.-C. (2006). Changes in some quality factors of frozen ginger as affected by the freezing storage conditions. *JSFA Journal of the Science of Food and Agriculture, 86*(10), 1439-1445.

Kirkland, B. S., Clarke, R., & Paul, D. R. (2008). A versatile membrane system for bulk storage and shipping of produce in a modified atmosphere. *Journal of Membrane Science, 324*(1–2), 119-127. doi: 10.1016/j.memsci.2008.07.001

Kok, R., & Raghavan, G. S. V. (1982). A Mathematical Model of the Controlled Atmosphere Storage of Apples Using The Marcellin System. *Canadian Institute of Food Science and Technology Journal, 15*(3), xvi. doi: 10.1016/S0315-5463(82)72451-4

Konar, E. M., Harde, S. M., Kagliwal, L. D., et al. (2013). Value-added bioethanol from spent ginger obtained after oleoresin extraction. *Industrial Crops and Products, 42*, 299-307. doi: 10.1016/j.indcrop.2012.05.040

Le, D. P., Smith, M., Hudler, G. W., et al. (2014). Pythium soft rot of ginger: Detection and identification of the causal pathogens, and their control. *Crop Protection, 65*, 153-167. doi: 10.1016/j.cropro.2014.07.021

Lee, Y. B., Kim, Y. S., & Ashmore, C. R. (1986). Antioxidant Property in Ginger Rhizome and Its Application to Meat Products. *Journal of Food Science, 51*(1), 20-23. doi:10.1111/j.1365-2621.1986.tb10826.x

Letizia, C. S., Cocchiara, J., Lalko, J., et al. (2003). Fragrance material review on linalool. *Food and Chemical Toxicology, 41*(7), 943-964. doi: 10.1016/S0278-6915(03)00015-2

Liplap, P., Boutin, J., LeBlanc, D. I., et al. (2014). Effect of hyperbaric pressure and temperature on respiration rates and quality attributes of Boston lettuce. *International Journal of Food Science & Technology, 49*(1), 137-145. doi:10.1111/ijfs.12288

Lopresto, C. G., Petrillo, F., Casazza, A. A., et al. (2014). A non-conventional method to extract D-limonene from waste lemon peels and comparison with traditional Soxhlet extraction. *Separation and Purification Technology, 137*, 13-20. doi: 10.1016/j.seppur.2014.09.015

Lu, M., Yuan, B., Zeng, M., & Chen, J. (2011). Antioxidant capacity and major phenolic compounds of spices commonly consumed in China. *Food Research International, 44*(2), 530-536. doi: 10.1016/j.foodres.2010.10.055

Majidi, H., Minaei, S., Almassi, M., & Mostofi, Y. (2014). Tomato quality in controlled atmosphere storage, modified atmosphere packaging and cold storage. *Journal of Food Science and Technology, 51*(9), 2155-2161. doi: 10.1007/s13197-012-0721-0

Martínez-Romero, D., Guillén, F., Castillo, et al. (2009). Effect of ethylene concentration on quality parameters of fresh tomatoes stored using a carbon-heat hybrid ethylene scrubber. *Postharvest Biology and Technology, 51*(2), 206-211. doi: 10.1016/j.postharvbio.2008.07.011

Mattos, L. M., Moretti, C. L., Jan, S., et al. (2014). Chapter 19 - Climate Changes and Potential Impacts on Quality of Fruit and Vegetable Crops. In P. Ahmad & S. Rasool (Eds.), *Emerging Technologies and Management of Crop Stress Tolerance* (pp. 467-486). San Diego: Academic Press.

McGuire, R. G. (1992). Reporting of objective color measurements. *HortScience, 27*(12), 1254-1255.

Misawa, K., Hashizume, K., Yamamoto, M., et al. (2015). Ginger extract prevents high-fat diet-induced obesity in mice via activation of the peroxisome proliferator-activated receptor δ pathway. *The Journal of Nutritional Biochemistry, 26*(10), 1058-1067. doi: 10.1016/j.jnutbio.2015.04.014

Morris, R. F. (1978). *Postharvest food losses in developing countries: a bibliography*: National Academies.

Mukherjee, P. K., Thomas, P., & Raghu, K. (1995). Shelf-life enhancement of fresh ginger rhizomes at ambient temperatures by combination of gamma-irradiation, biocontrol and closed polyethylene bag storage. *Annals of Applied Biology, 127*(2), 375-384. doi:10.1111/j.1744-7348.1995.tb06681.x

Naik, R., Ambrose, D. C. P., Raghavan, G. S. V., & Annamalai, S. J. K. (2014). Enhancing shelf life of minimally processed multiplier onion using silicone membrane. *Journal of Food Science and Technology-Mysore, 51*(12), 3963-3969. doi:10.1007/s13197-012-0898-2

Nair, K. P. P. (2013). 23 - The Postharvest and Industrial Processing of Ginger *The Agronomy and Economy of Turmeric and Ginger* (pp. 433-452). Oxford: Elsevier.

Natarajan, C. P., Bai, R. P., Krishnamurthy, M. N., et al. (1972). Chemical composition of ginger varieties and dehydration studies on ginger. *Journal of Food Science and Technology, India, 9*(3), 120-124.

National Center for, C., & Alternative, M. (2008). Ginger.

Navarro, S. (2012). The use of modified and controlled atmospheres for the disinfestation of stored products. *Journal of Pest Science, 85*(3), 301-322. doi:10.1007/s10340-012-0424-3

Park, M., Bae, J., & Lee, D. S. (2008). Antibacterial activity of [10]-gingerol and [12]-gingerol isolated from ginger rhizome against periodontal bacteria. *Phytotherapy Research, 22*(11), 1446-1449. doi:10.1002/ptr.2473

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988a). Compositional changes in ginger rhizomes during storage. *Journal of the American Society for Horticultural Science, 113*(4), 584-588.

Paull, R. E., Chen, N. J., & Goo, T. T. C. (1988b). Control of weight-loss and sprouting of ginger rhizome in storage. *HortScience, 23*(4), 734-736.

Planella, I., & Myrtle Seepersad, I. P. (1990). *Proceedings of a Workshop on Post Harvest Handling of Horticultural Commodities for Export*: Inter-American Institute for Cooperation on Agriculture.

Plasse, R. (1986). *Vegetable storage, respiration and design criteria in a membrane storage system.* (ML34442 M.Sc.), McGill University (Canada), Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Plotto, A. (2002). Ginger Postharvest Operations. *INPhO compendium*.

Prasad, J., & Vijay, V. K. (2005). Experimental studies on drying of Zingiber officinale, Curcuma longa l. and Tinospora cordifolia in solar-biomass hybrid drier. *Renewable Energy, 30*(14), 2097-2109. doi: 10.1016/j.renene.2005.02.007

Pruthi, J. S. (1976). *Spices and condiments*.

Raghavan, G. S. V. (2005). Refrigerated and controlled/modified atmosphere storage. *Processing Fruits, Science and technology*, 23-52.

Raghavan, G. S. V., Gariépy, Y., Thériault, R., et al. (1984). System for controlled atmosphere long-term cabbage storage. *International Journal of Refrigeration, 7*(1), 66-71. doi: 10.1016/0140-7007(84)90057-4

Raghavan, G. S. V., Tessier, S. & Chayet, M., et al. (1982). Storage of vegetables in a membrane system. *Transactions of the ASAE, 25*(2), 433-436.

Raghavan V, Gariepy, Y., & Vigneault C. (1996). Refrigerated and controlled modified atmosphere storage. *Processing fruits: science and technology*, 135-167.

Ratti, C., Raghavan, G. S. V., & Gariépy, Y. (1996). Respiration rate model and modified atmosphere packaging of fresh cauliflower. *Journal of Food Engineering, 28*(3), 297-306. doi: 10.1016/0260-8774(95)00044-5

Ravindra, N., Ambrose, D. C. P., Raghavan, G. S. V., et al. (2007). Role of silicone membrane storage on increased shelf life of minimally processed multiplier onion. *Proceedings of the International Agricultural Engineering Conference, Bangkok, Thailand*.

Ravindra, N., & Kailappan, R. (2007). Role of silicone membrane in increasing the shelf-life and quality of tomatoes during storage. *Journal of Food Science and Technology, 44*(3), 301-306.

Rhim, J. W. (2007). Potential use of biopolymer-based nanocomposite films in food packaging applications. *Food Science and Biotechnology, 16*(5), 691-709.

Riad, G. (2004). Atmosphere modification to control quality deterioration during storage of fresh sweetcorn cobs and fresh-cut kernels. (3146245 Ph.D.), University of Florida, Ann Arbor. ProQuest Dissertations & Theses Full Text database.

Sabogal-Guáqueta, A. M., Osorio, E., & Cardona-Gómez, G. P. (2016). Linalool reverses neuropathological and behavioral impairments in old triple transgenic Alzheimer's mice. *Neuropharmacology, 102*, 111-120. doi: 10.1016/j.neuropharm.2015.11.002

Sabulal, B., Dan, M. J., Kurup, R., et al. (2006). Caryophyllene-rich rhizome oil of Zingiber nimmonii from South India: Chemical characterization and antimicrobial activity. *Phytochemistry, 67*(22), 2469-2473. doi: 10.1016/j.phytochem.2006.08.003

Saltveit, M. E. (2004). Respiratory metabolism. *The commercial storage of fruits, vegetables, and florist and nursery stocks. Agriculture Handbook, 66*.

Shaista, J. K., Aneela, F., Nasreen, Z., et al. (2010). Effect of different stabilizers on the antibacterial activity of "ginger garlic paste". *J.Appl. Sci. Environ. Manag., 13*, 103-109.

Shchipunov, Y. (2012). Bionanocomposites: Green sustainable materials for the near future. *Pure and Applied Chemistry, 84*(12), 2579-2607. doi:10.1351/PAC-CON-12-05-04

Shukla, Y., & Singh, M. (2007). Cancer preventive properties of ginger: A brief review. *Food and Chemical Toxicology, 45*(5), 683-690. doi: 10.1016/j.fct.2006.11.002

Śledź, M., Nowacka, M., Wiktor, A., et al. (2013). Selected chemical and physico-chemical properties of microwave-convective dried herbs. *Food and Bioproducts Processing, 91*(4), 421-428. doi: 10.1016/j.fbp.2013.02.010

Somogyi, L., Ramaswamy, H. S., & Hui, Y. H. (1996). *Processing Fruits: Science and Technology*: Taylor & Francis.

Standards, B. B. O. I. (2008). Ginger, whole and ground—specification *Spices and condiments*. Spices and Condiments Sectional Committee, New Delhi.

StatsCanada. (2013). 091011 Ginger, neither crushed nor ground.

Stewart, O. J., Raghavan, G. S. V., Golden, K. D., et al. (2005). MA storage of Cavendish bananas using silicone membrane and diffusion channel systems. *Postharvest Biology and Technology, 35*(3), 309-317. doi:10.1016/j.postharvbio.2004.10.003

Sultana, S., & Ali, M. (2015). Chemical composition of volatile oil of the rhizome of Zingiber officinale roscoe and its antimicrobial activity. *World j. of pharmacy and pharmaceutical sci, 4*, 741-752.

Sutarno, H., Hadad, E.A., & Brink, M. (1999). *Plant resources of South-East Asia, No.13. Spices*. Leiden: Backhuys Publishers.

Thompson, A. (1971). Storage of mango fruits. *Tropical Agriculture, 48*(1), 63-&.

Touba, E. P., Zakaria, M., & Tahereh, E. (2012). Anti-fungal activity of cold and hot water extracts of spices against fungal pathogens of Roselle (Hibiscus sabdariffa) in vitro. *Microbial Pathogenesis, 52*(2), 125-129. doi: 10.1016/j.micpath.2011.11.001

UN-News. (2013). World population projected to reach 9.6 billion by 2050. Retrieved from http://www.un.org/en/development/desa/news/population/un-report-world-population-projected-to-reach-9-6-billion-by-2050.html

Unni, L. E., Chauhan, O. P., & Raju, P. S. (2015). Quality changes in high pressure processed ginger paste under refrigerated storage. *Food Bioscience, 10*, 18-25. doi: 10.1016/j.fbio.2014.12.005

Varrò, M. T. (1800). The Three Books of M. Torentina Varro Concerning Agriculture, T. Owens (trans.): The University Press, Oxford.

Vigneault, C., (1994). *Techniques for controlled atmosphere storage of fruits and vegetables*. [Ottawa]: Research Branch, Agriculture and Agri-Food Canada.

Vijendra Kumar, N., Murthy, P. S., Manjunatha, J. R., et al. (2014). Synthesis and quorum sensing inhibitory activity of key phenolic compounds of ginger and their derivatives. *Food Chemistry, 159*, 451-457. doi: 10.1016/j.foodchem.2014.03.039

Wang, Y. S., Tian, S. P., & Xu, Y. (2005). Effects of high oxygen concentration on pro- and anti-oxidant enzymes in peach fruits during postharvest periods. *Food Chemistry, 91*(1), 99-104. doi:10.1016/j.foodchem.2004.05.053

Wangcharoen, W. (2012). Development of ginger-flavoured soya milk ice cream: Comparison of data analysis methods. *Maejo International Journal of Science and Technology, 6*(3), 505-513.

Weiss, E. A. (2002). *Spice crops*: CABI.

Wills, R. H. H., Lee, T. H., Graham, D., et al. (1981). *Postharvest. An introduction to the physiology and handling of fruit and vegetables*.

Wolf, B. (2016). Confectionery and Sugar-Based Foods *Reference Module in Food Science*: Elsevier.

Yusof, N. (1990). Sprout inhibition by gamma-irradiation in fresh ginger (*zingiber-officinale roscoe*). *Journal of Food Processing and Preservation, 14*(2), 113-122. doi:10.1111/j.1745-4549.1990.tb00833.x

CHAPTER V

SUMMARY AND CONCLUSION

Every year, countries all over the world face issues such as of food wastage and postharvest losses. Even though the production of agricultural produce is high in developed countries, so are the food losses. These losses are easily preventable, and in many cases, it is just a matter of using an appropriate method of postharvest storage. Controlled atmosphere storage (CAS) and Modified atmosphere storage (MAS) are to separate but interlinked processes used for the storage of fresh fruits and vegetables. A silicone membrane system unit that created a modified atmosphere over the storage period was designed and used to study the characteristics of ginger stored under such modified atmosphere at ambient temperature conditions.

The initial objective of this study was to characterise the available silicone-based membranes for the storage of fresh produce. In membrane-based systems, the properties of silicone membrane, affect the storage period and, the composition of gases in the storage chamber. The permeability of the membrane determines the composition of the storage environment due to different selectivity for different gases. Five types of membranes and their physical parameters were studied. The MSM and CSM membranes have been used for a few decades in several storage operations and were used as references. The GA, GB, and GC membrane had lower tensile strength but good surface structure. The GA and, GB membranes had a lower permeability to CO_2, and O_2 than that of the GC membrane. The GC membrane had a higher selectivity ratio for carbon dioxide gas. Hence, out of the five membranes, three (MSM, CSM, and GC) were selected for the storage of ginger.

The second objective of this study was to examine the storage of ginger in membrane system under ambient storage conditions. Such systems, require a lower oxygen concentration and a higher carbon dioxide concentration. The experiment was designed using response surface design methodology based on two factors viz. the storage duration and the desired oxygen concentration at the end of the storage period. The duration of storage ranged between 7 to 21 days and the membrane area for the storage was dependent on its permeability and ranged between 0.7 cm^2 to 6 cm^2. Over a period of seven days, a steady level of the respiratory gases was achieved, though the concentration did not reach the desired levels over the storage period. A larger membrane area, larger free volume to stored mass ratio, and longer storage period, may help address the problems and help in long term storage of ginger. Another issue faced was that, for the longer storage period, the ginger rhizome developed buds and some rhizomes were damaged due to mold growth. The percent mass loss and the total color difference were lesser in the case of ginger stored with the MSM and GC membranes. Both these membranes showed steady changes in the respiratory gas concentrations and can be used for other fresh produce storage. Overall, these systems have the potential to reduce food wastage when cold-chain is not accessible for the storage of fresh crop produces.

- **Future work to be done:**

  - Investigate the storage of ginger at controlled lower temperatures (< 23 °C) and regulated pressure conditions for a longer storage.
  - The effect of pre-treatment of ginger using chemicals to coat the ginger before storage needs to be studied to prevent microbial damage
  - The use of these silicone-based membranes needs to be studied for a variety of crops stored on a large scale for a long duration at higher CO_2 and lower O_2 levels.