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Application of silicone membrane technology to increase quality and shelf life of fruits and vegetables: a review

Nair Chithra Harinarayanan[1] and Maya Raman[2*]

1, Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi-682506, Kerala, India
2, Department of Food Science and Technology, Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi-682506, Kerala, India

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***Corresponding author:**
Department of Food Science and Technology, Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi-682506, Kerala, India.
Email: mayaraman@kufos.ac.in; ramanmaya@gmail.com

ABSTRACT

Purpose: The prime aim of food storage and preservation is to protect and preserve food; and hence, extend its shelf life with minimal losses. Amongst the various factors involved to increase the shelf life and preservation, packaging plays a very critical role by providing a good physical barrier to oxygen, moisture, microorganisms, and other volatiles. Certain perishable food products require modified and controlled atmospheric packaging in order to keep them fresh, sterile, clean, and safe. The purpose of this study is to analyze and understand the use of silicone membrane technology in preserving the quality and extending the shelf life of fruits and vegetables. **Main findings:** The silicone membrane system (SMS) being a method of controlling atmospheric composition in fruits and vegetable storage, it was found that the shelf life and quality of the products were maintained to its best through selective membrane permeability and product respiration. The SMS allows diffusion of gases, at different rates, which is dependent on its physical and chemical properties and can be technically controlled compared to conventional Controlled Atmospheric systems. **Limitations:** This technology has been limited only to laboratory scale, and needs to be commercialized. Another big limitation is its high cost. Moreover, certain fruits required pre-processing before being kept in chambers with silicone windows. **Directions for Future Research:** This system needs to be studied in a more appropriate way and in a more cost-effective manner, such that it can be commercialized and made available for farmers at low cost to protect their produce.

INTRODUCTION

India is the second-largest producer of fruits and vegetables in the world after China. According to the Horticulture Statistics division (2021), the total horticultural production in India in the year 2020-21 is estimated to be 329.86 Million Tonne, out of which only 1-2% were used for processing and the rest were consumed either whole or were exported after minimal processing. It was estimated that the post-harvest loss that accounted for about 30% of the production, was chiefly attributed to the poor post-harvest practices (Yahaya & Mardiyya, 2019).

Fruits and vegetables, due to the high percentage of moisture and water activity, are highly perishable and more prone to spoilage; therefore, it is highly pertinent to immediately pack and preserve these under cold/ refrigerated/ Controlled Atmospheric conditions or subject to minimal processing. Packaging fresh fruits and vegetables are one of the most important, extensively researched, and complicated steps within a postharvest handling system. The conventional methods of packaging fresh produce include bags, crates, hampers, baskets, cartons, bulk bins, and palletized containers with the ease of handling, transporting, and marketing. However, even under such situations, the chances of produce being spoiled are high, due to chilling injury, ethylene induced problems, etc. This made it necessary to find an alternative to minimize spoilage and enhance the shelf life, which paved the way for the use of various kinds of innovations such as the utilization of membranes/ films in food preservation. Furthermore, the packaging material should be recyclable/ biodegradable, should have sales appeal, reduce wastage, and should be applicable to a variety of produce. The common methods used to maintain the quality of freshly harvested produce include low temperature with the regular atmosphere (RA), low temperature with regular atmosphere and high RH atmosphere (HRA), low temperature with high RH, and modified / controlled atmosphere storage.

The nutritional and economic value of fruits and vegetables

Fruits and vegetables are considered to be of high importance in the diet, because of their high concentrations of dietary fibre, minerals, especially electrolytes, vitamins, and many phytochemicals, especially antioxidants (Slavin & Lloyd, 2012). Sufficient intake of fruits and vegetables has been associated with reduced risk of a variety of diseases and acts as free radical scavengers (Kaur & Kapoor, 2001). Fruits and vegetables have y low starch, instead of containing a lot of fibre and water, which contributes to satiety eight (Tohill et al., 2004). According to Southon, (2000), when fruits and vegetables rich in carotenoids are consumed on a high scale, it helps in maintaining the cholesterol level in the blood by reducing oxidative damages and causing an increase in LDL oxidation resistance. Diet rich in fruits and vegetables were found to restrict the amount of saturated and total fat, which reduced the systolic blood pressure by 11 mm Hg and diastolic blood pressure by 6 mm Hg (Appel et al., 1997).

For developing countries like India, global agricultural trade is of high significance. The demand for food is increasing rapidly due to the increasing population. Fruits and vegetables play an important role in the diet of a person by providing the essential vitamins, dietary fibre, and minerals. According to Food and Agriculture Organization (2015) stated that among developed countries, the US tops the list in international trade of fruits and vegetables accounting for approximately 18% of the $40 billion (USD) in fresh produce world trade. Developing countries rely more on agriculture as well as the demand for fresh horticultural products is increasing day by day. This has also helped in promoting the growth of local farmers, thus, creating an increase in their income. Fruits and vegetable production, processing, and marketing provide enormous opportunities to the youth today since they require small amounts of land, are more convenient in using technologies, and also high profits within a short period (Schreinemachers et al, 2018). One of the major threats faced by the farmers is that of crop pests and diseases and this can be lowered through the use of protected cultivation systems. Postharvest loss of fruits and vegetables are large and are estimated to be in the range of 30-40% of the farm-produced volumes (FAO, 2011). It is estimated that India incurs a loss of over 2 lakh crore each year owing to lack of food processing units, modern cold storage systems, and attitude to tackle the post-harvest losses (ASSOCHAM, 2013). Hence, to improve this situation, there must be proper investment in cold-storage systems, logistics, and the market for high-value perishable foods.

Different types of storage systems

Fruits and vegetables respire after the harvest. This respiration rate (RR) depends on several factors such as O_2, temperature, carbon dioxide, humidity, mechanical injury, diseases, and pest infection (Khan et al., 2017). Different types of storage systems that are generally used for the purpose of storing fruits and vegetables are in-situ/field storage, sand, and coir, pits, clamps, Cellar/root cellars, ventilated storage systems (Natural and forced air ventilation systems), evaporative cool chambers, modified and controlled atmosphere systems (Kaur et al., 2021).

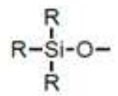
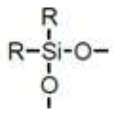
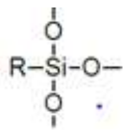
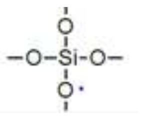
Modified Atmospheric Packaging (MAP) and Controlled Atmospheric System (CA) are the most common methods adopted for preserving the quality of fresh fruits and vegetables. In MAP, the various gases (CO_2, O_2, N_2), are controlled to enhance the shelf life of the product with minimal losses. The levels of gases vary with the type of food being packed. In the case of fruits and vegetables, CA is preferably practiced. In CA, the oxygen is generally decreased and the levels of carbon dioxide are increased. Many types of CA are available for commercial storage of fresh fruits and vegetables. Of the various technologies developed, the application of the Silicone Membrane System (SMS) gained considerable attention in the controlled atmospheric system. Membrane technologies have been widely used as a separation method, and now emerging as an excellent food packaging method, especially for fruits and vegetables. In this system, conditions similar to CA are obtained through two simultaneous processes such as respiration and membrane permeability. The silicone membrane system was reported to have successful applications in the case of both modified and controlled atmospheric storage and is a promising approach for long-term storage. Furthermore, this system is economical has the ability to provide high relative humidity, proper gas composition, and can be operated at low temperature.

All about silicone

Silicones form a highly versatile class of polymers that are in the form of fluid, gums, grease, rubbers, resins, copolymers, in food contact surfaces; and as additive in polymers (Fig. 1; Geueke, 2015). These are generally water repellant, flexible, versatile, thermo stable, non-reactive and highly gas permeable. The backbone of silicone is silicon (Si) with oxygen and two organic groups. These are also termed as siloxanes, siloxane oligomers, or polysiloxanes. The organic groups could be methyl, ethyl or phenyl. Several Si-O backbones can be linked together to form huge variety of silicones (M, D, T, Q) based on the number of Si-O bonds per structural unit (Table 1).

Fig. 1. Examples of silicone contacting food contact surfaces (Courtesy: Nerissa's ring, Piulet, Didriks, Greg and Sam Howzit, www. Flickr.com) (Geueke, 2015).

Table 1. Structural units of silicone

Structural units	Functionality	Simplified notation
	Monofunctional	M
	Difunctional	D
	Trifunctional	T
	Tetrafunctional	Q

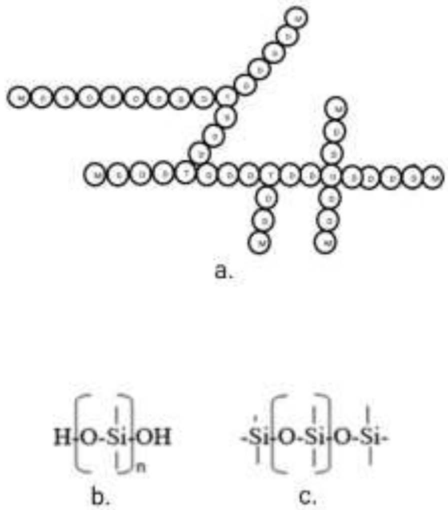


Fig. 2. Schematic illustration of a) cross-linked silicone resin b) Hydroxy terminated polydimethylsiloxane c) methyl terminated polydimethylsiloxane.

Difunctional (D-units) are linear, with may or may not monofunctional M-units at the terminal ends of the siloxane molecules. Other two structures aid in cross-linking of the polymer. The most common silicone is simple, unmodified and non-copolymerized polydimethylsiloxane with hydroxy or methyl at the terminal ends (Fig. 2).

Silicone finds wide industrial and household applications. These are also widely used in food packaging. These are used as additives in plastics to improve processing, molding, fire resistance, and surface properties. These are also used in the paper industry to prevent foaming, as an additive in the finishing process of paper and tissues, and for de-inking during paper recycling. The other applications include coatings on corks for alcoholic beverages and liners for beverage bottles and other containers. These are also used as food additives. The use of silicone membranes/ films in food packaging and extended shelf life was a remarkable application and a turning point.

Silicone Membrane System

SMS is a controlled ventilation system and is defined as a sealed chamber equipped with a silicone elastomer membrane of selective gas permeability (Raghavan et al., 1982). Figure 3 shows a silicone membrane window, where it consists of fine Tergal net (52-54g/m^2), covered with a uniform-thin layer (about 90µm) of silicone rubber (dimethylpolysiloxane or polydimethylsiloxane) (Naik & Kailappan, 2007). At a given temperature, the amount of gas diffusion through the membrane depends on the surface area, gas partial pressure difference across the membrane and its permeability. At 1 atm (1Pa), the permeability of carbon dioxide, oxygen and ethylene were 1750 (80 nmol/m/Pa), 320 (15 nmol/m/Pa) and 700 (32 nmol/m/Pa) L/d-m^2-Atm, respectively (Gariepy et al., 1988). The membrane has the ability to permit selective passage of gases at different rates according to its physical and chemical properties. The membrane is characterized by its gas diffusion rate and its selectivity. The main advantages of the silicone membrane system are (Naik et al., 2012):

a. Lower operating cost due to fewer controls and less maintenance during operation
b. Lower refrigeration cost attributable to lower respiratory activity
c. The high permeability of the membrane to ethylene
d. Low permeability to water vapor.

The area of the membrane required can be calculated using the equation (Gariepy & Raghavan, 1986; Stewart et al., 2005)

A = respiration rate × m_a/ PCO_2 × CO_2

Where,

A is the area of the silicone membrane in m^2, the respiration rate of the product stored under CA/ MA is measured in liters CO_2 consumer/kg/day, m_a is the mass of the stored produce in kg, PCO_2 is the permeability of the silicone membrane to CO_2 in nmol/m_2/Pa and CO_2 is the desired CO_2 partial pressure difference across the membrane in Pa.

Commercially used CA storage system that utilizes the silicone membrane is as follows:

- The Pallet Package
- The Marcellin system and
- Atmolysair system.

i) **The Pallet Package system**

Figure 4 shows "The Pallet Packaging System" developed by Marcellin in 1978 and this system consists of a pallet box wrapped in a polyethylene bag of heavy gauge, with a silicone membrane window installed to regulate gas exchange. It has to be well-spaced, in order to work properly, so as to reduce the floor space of the storage room. Though its application was developed for long-term storage, its limitations made it suitable for medium storage as well as for the transportation of the produce. The advantage of this system is that it can be easily manipulated and a part of the product can be marketed without affecting the remaining pallet system. The disadvantage is that a lot of manpower and time is required to wrap, unwrap, and handling of the pallets (Gariepy et al., 1988).

ii) **The Marcellin System**

The Marcellin System (Fig. 5) helps to regulate the CA condition inside the storage room. It consists of a series of parallel connected rectangular boxes/ bags of silicone rubber. The number of bags depends upon the capacity of the storage room, the respiration properties of the products, and the storage temperature. The units are installed either outside or inside of the cold room system (Guertin, 1979).

iii) **The Atmolysair System**

The Atmolysair System (modified version of Marcellin system, developed in Canada**)** consists of a set of panels for gas diffusion which are enclosed in an airtight container with two separate paths for airflow and a control panel, as shown in Figure 6. These panels are arranged side by side so that the outside air and the modified air from the storage chamber flow without direct mixing on the opposite sides of the membrane. In order to maintain the air circulation, two centrifugal blowers operated by a timer are used. The composition of gas can be periodically analyzed and the timer of the blower can also be adjusted. The surface area of the membrane to be used is previously computed and outlined, and it has been successfully implemented by Canadian cabbage producers. The advantages of this system over the Marcellin system include ease of operation, better gas exchange, and complete automation (Lanson et al., 1985).

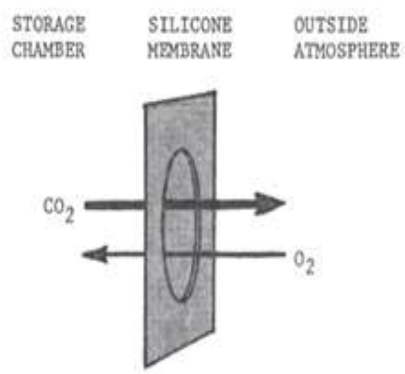


Fig. 3. Silicone Membrane Performance (Schell, 1986).

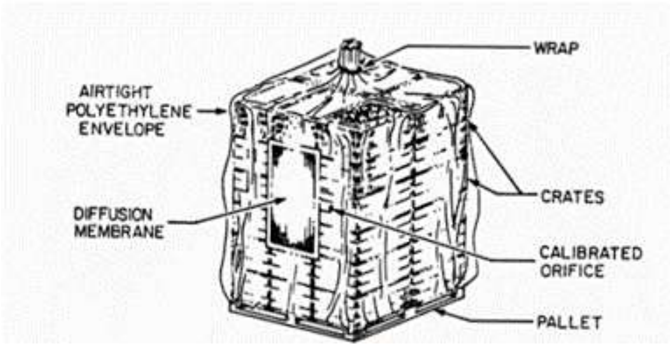


Fig. 4. The Pallet Packaging System for CA system (Gariepy et al., 1988).

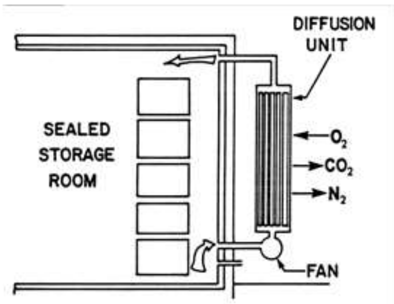


Fig. 5 The Marcellin System for CA system (Raghavan et al.,1996).

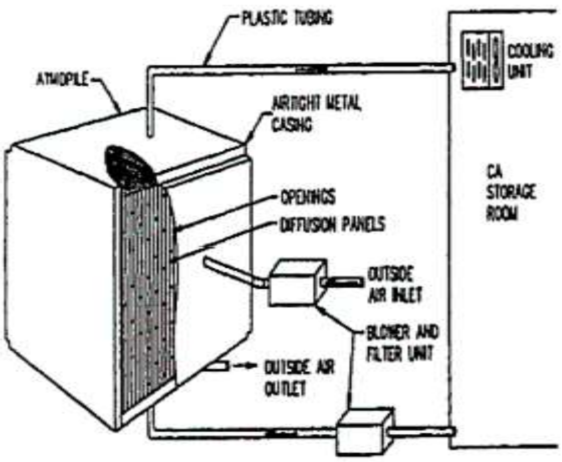


Fig. 6. The Atmolysair System (Raghavan et al.,1996).

Application of silicone membrane system in increasing the shelf life of fruits and vegetables

Though the application of silicone membrane in extending the shelf-life of fruits and vegetables was successful at a laboratory scale, not much of the work has been reported on its potential application at the commercial level. The technology was tried successfully at a laboratory scale on various fruits and vegetables.

Leeks and Celery

The chambers used for the experiment by Gariepy et al. (1988), were made of sections of PVC pipe and the ends of each unit were closed with a square lid of clear acrylic with Neoprene gaskets to which silicone membrane was held in a window-like fashion. The Alaskan leeks (*Allium porrum* L. cv. Alaska) were stored under four different CA compositions for 133 days and clean-cut celery (*Apium graveolans* cv. Clean cut) under 3 different compositions for 71 days. The membrane surface area required was calculated by various statistical methods and CA compositions were analyzed using gas chromatography for complete experiment durations.

The results emphasized that the progression of CO_2 and O_2 concentration followed a characteristic trend of SMS and the concentration in the CA chamber was dependent upon the membrane surface area. It was also observed that several factors such as level of pre-storage preparation, cultivar, geography, and pre-storage treatments affected the gas concentrations maintained inside the chambers. From the experiment, it was found that the smallest membrane area (36 cm^2), with 9% CO_2 provided greater shelf life of 145 days for leek and a membrane area of 49 cm^2 with 5.5% CO_2 extended the shelf life of celery to about 71 days.

Onions

Pungent Multiplier Onions (*Onion aggregatum*) were graded and prepared at a low temperature. The onions were manually peeled, sliced, and dipped in cold water for minute and excess moisture was removed. The studies were carried out at two different temperatures: ambient temperature (30±2ºC; 60% RH) and at low temperature (5±1ºC; 90% RH). Polyethylene Tetra Phthalate (PET) containers with silicone membrane windows were used for the storage studies (2 to 10% CO_2). The treatment done at regular atmosphere was used as control. These samples were then measured for their flavor, visual score and also using statistical studies. Gas analysis and respiration rates were also analyzed.

Though a reduction in the pungency of the minimally processed onion was observed with the storage time, it was within acceptable limits of 14µ mol pyruvic acid. All the samples stored in ambient temperature (30±2ºC, 60% RH) were found unacceptable in the shelf life study conducted and those stored with MA storage at low temperature were found to be highly acceptable. At low temperature, the shelf life was 5 days, whereas the combination of MA with silicone membrane at low temperature gave the extended shelf life of 14 days. The respiration rate for the diced, sliced, and dipped onions were found to be 23.4, 15.6, 10 mg CO_2 $kg^{-1}h^{-1}$ at 5±1ºC (RH=90%) and 140, 110, 60mg CO_2 $kg^{-1}h^{-1}$ at 30±2ºC (RH=60%) and for fresh multiplier onion, it was 5, 10mg CO_2 $kg^{-1}h^{-1}$ at 5±1ºC and 30±2ºC. According to shelf life and sensory evaluation studies, only peeled onion could be stored, as sliced and diced did not give adequate shelf life. This technology hence can be used to increase the shelf life of minimally processed multiplier onions. (Naik et al., 2012).

Pomegranates

According to Srivastava and Said (2019), *Bhagwa* variety of pomegranate was used for the study with all the pre-processing required and then dipped in 0.2% bavistin for 1 min

(Dhumal et al., 2014; Allam et al., 2017). Modified atmospheric packages of 200, 300- gauge high-density polyethylene (HDPE) packages and PET jars with silicone membrane were used to study the shelf life with 10 different treatments (ventilation of 0.06% and 1%; Membrane window area of 1 cm^2, 2 cm^2, and 3 cm^2) at ambient and refrigerated conditions and named from T_1 to T_9, with T_{10} as control.

T1: 200-gauge HDPE package without ventilation
T_2: 200-gauge HDPE package with 0.06% ventilation
T_3: 200-gauge HDPE package with 0.1% ventilation
T_4: 300-gauge HDPE package without ventilation
T_5: 300-gauge HDPE package with 0.06% ventilation
T_6: 300-gauge HDPE package with 0.1% ventilation
T_7- Silicone membrane with 1 cm×1 cm (1 cm^2) window area
T_8- Silicone membrane with 1.41cm×1.41cm (2 cm^2) window area
T_9- Silicone membrane with 1.71cm×1.71cm (3 cm^2) window area

They were later analyzed for texture, color, ascorbic acid, titratable acidity, weight loss, and overall acceptability.

It was found that the respiratory rate of pomegranate followed a climacteric pattern and the respiration peak of fruits after storage at 10ºC (15.03 mg CO_2 kg^{-1} h^{-1}) was lower compared to the fruits stored at ambient temperature (25ºC±2, 44.6 mg CO_2 kg^{-1} h^{-1}). The rate of respiration is inversely proportional to the product's shelf life. The respiration rate was reduced by limiting the oxygen, which delayed the process of oxidative breakdown.

The best texture of pomegranate fruits was obtained with 200 and 300 HDPE packages with a shelf life of 60 days for both the packages in ambient conditions. The best texture for those at 10°C was obtained with 200 and 300 HDPE packages with a shelf life of 96 days, while the physiological weight loss was just 4-5% for 100-day storage study for 200-gauge HDPE. Silicone membrane systems at ambient gave a maximum peak force of 2080.3 g with a shelf life of 25 days, while at 10°C the maximum peak force was obtained at 2265.8 g with a shelf life of 65 days, where peak force usually is described as the point where fracturing starts. The physiological weight loss was just 3% for those stored in silicone membrane for up to 100 days. The color of the fruits was found to be close to the fresh ones. Total soluble solids of those stored at ambient temperature were less (19.33%) compared to those stored at 10ºC with silicone membrane. There was also a considerable increase in the reducing sugars of the fruits from 7.86% (fresh) to 12.76% (300-gauge HDPE) at ambient conditions while at 10°C it was 12.24% for those with silicone membrane. However, there was a decrease in the ascorbic acid content, which may be attributed to the oxidative reduction of vitamin C in presence of molecular oxygen by the ascorbic acid oxidase enzyme (Pruthi et al., 1984).

Cavendish Banana

Banana is basically a tropical fruit that is beneficial for health. They are usually harvested before getting fully matured for domestic consumption and are stored at room temperature. However, they get easily deteriorated due to the quick ripening process (Marriot & Palmer, 1980). MA storage systems were found to be one of the methods to prolong the shelf-life of the bananas, through the use of LDPE packages. Further modifications were made by Stewart et al. (2005), by the addition of ethylene absorbers like potassium permanganate with polyethylene films. Storage studies were done for both silicone membrane and diffusion channel for pre-climacteric bananas (*Musa acuminata*, cv. Cavendish) of commercial maturity, at 15ºC. The respiration rates, color, titratable acidity, total sugars, firmness, and overall acceptability were evaluated by the group.

The best storage was achieved with a silicone membrane of area 50.29 cm^2 with respiration rate less than 60% of that of regular atmosphere and was of superior quality. The shortest area of silicone membrane and shortest length of diffusion channel (4cm) was found to be the most effective and those kept in chambers with high CO_2 levels (>7%) suffered skin discolorations and development of ethanol atmospheres in the chambers, indicating fermentation and reduced shelf life. The fruits kept in MA storage showed an increase in color, total solids, total sugars, titratable acidity, and a decrease in firmness. The fruits kept under the diffusion channel had lower values for total soluble solids than those treated using membranes and ripe controls. There was no change in titratable acidity of fruits treated using diffusion channel and silicone membrane treatments. The mass loss of fruits was very less ($P < 0.05$) than those stored under regular atmospheric conditions. Fruit stored under silicone membrane showed a mass loss of 2-3.5%, those in diffusion channel lost 4-7%, while those under regular atmospheric conditions lost 12.5%. Weight loss, peel color, and storage life were affected by the humidity levels of the storage. The sensory evaluation scores showed that the fruits stored under the silicone membranes were more acceptable than those stored using diffusion channels. Those stored with the smallest area of the membrane and shortest diffusion channel were rated well compared to those brought from stores.

Cabbage

Cabbages (*Brassica oleracea* var. capitata) are one of the most widely used vegetable crops in the world with dense-leaved heads, which are rich in antioxidants, proteins, vitamins, and other nutrients. Leaf-yellowing and wilting are major problems affecting its commercial value.

Gariepy et al., in (1985), selected chambers made from PVC with two extremities close with a square lid of Plexiglass, and silicone membrane was attached to this lid in a window-like fashion. Neoprene gaskets were also used on both ends to ensure complete airtightness. The respiration rate of the cabbage was calculated as 60% of its value at regular atmosphere (RA) at the same temperature. The temperature was set at 1.5°C. The parameters analyzed for those under Controlled Atmosphere (CA) were relative humidity level, air temperature, gas composition, Respiration rate (RR), Respiratory Quotient (RQ), storage, visual quality, trimming, total mass loss, and physiology.

It was observed that the CO_2 level in the chambers was maintained below the designed values of 5% and at the end of the experiments, the ethylene levels in the chambers were around 3 ppm. The RR of the cabbages under the CA storage 2.1 mg of CO_2/kg-h and RQ of 0.6. The final visual quality of the cabbages stored under CA was excellent compared to those stored in a regular atmosphere; because it had slight yellowing and browning of the outer leaves, minimal superficial molding and rotting, and also better color retention. The total mass loss for those in CA was at a level of 0.05, which is significantly lower. Visual observations suggested that these cabbages stored in CA had higher chlorophyll, water, and sugar contents than those stored in RA. The cabbage was stored for 159 days in RA with a total mass loss of 39% and under CA with a total mass loss of 17% for 265 days.

Carrots

Carrots are usually harvested in September and October and stored for up to 6 months under refrigerated conditions at a temperature of 1ºC. Despite the low-temperature storage, it caused storage rot of carrots caused by *Sclerotinia sclerotiorum* and also attacked other carrots stored along with it. In the study done by Reeleder et al. (1989), the carrots from Quebec and

Florida were used for the study, and trials were carried out by keeping at temperatures of 1±1ºC. Five different atmospheres were used to compare: High relative humidity (HRA), unadjusted cold room atmosphere (RA), and three atmospheres with modified O_2 and CO_2 concentrations. The number of carrots to be stored in a container with an MA atmosphere was determined by using a respirometer (which measures the respiration rate (RR). PVC chambers with ends open were used for the study for RA, covered with 4 mils perforated plastic for HRA and those with silicone membranes for the modified atmospheres.

The respiration rate revealed that the O_2 concentrations decreased across the experimental treatments as the CO_2 concentrations increased. The O_2 decreased for all the treatments and the mean O_2 values obtained were 3.73, 4.47, and 3.03% respectively.

Due to the reduction in O_2 and increase in CO_2 concentration, the number of rejected carrots decreased and no. of acceptable carrots increased and no ethylene was detected in any of the chambers. Those stored at high humidity and cold rooms suffered the greatest percentage loss due to condensation of moisture inside the plastic containers that were sealed at the end. As the CO_2 levels were modified, the losses were much less and for inoculated carrots, the mass loss % varied from 3-7%. It was also seen that the modified CO_2 treatments provided better control of sclerotinia rot rather than cold temperature and high humidity treatments. The work done by the shear apparatus indicated that greater work was required for carrots subjected to high humidity treatments as compared to other treatments. The sensory evaluation stated that the carrots treated with 3.03% CO_2 and 4.57% O_2 were similar to carrots purchased from the store.

Jackfruit

Jackfruits (*Artocarpus heterophyllus* Lam.) is one of the major tropical fruit found in the rainforests of India, Bangladesh, Srilanka, Southern China, Australia, Brazil, Surinam, Mexico, Hawaii, and Southern Florida (Samaddar, 1985), which is mostly used for curry preparations when unripe and as a dessert when ripe. Jackfruit bulbs in pre-cut form provides great convenience for the consumers and also if assisted with special provisions for storage can be used for transportation from production site to remote places. MAP techniques were found to reduce decay and maintain its freshness and other quality attributes.

In the experiment done by Saxena et al. (2008), jackfruits were deseeded and cut into uniform slices. Two-thirds of the total fruit was washed with cold chlorinated water of 30ppm and this was further divided into 2 segments. Half of the produce were given pretreatment (T_1) in a post-harvest solution of $CaCl_2$ (1% w/v), ascorbic acid (0.02% w/v), citric acid (1% w/v) and sodium benzoate (0.045% w/v) for 30min (1:2), while remaining portion was pretreated (T_2) with solution of $CaCl_2$ (1% w/v) and ascorbic acid (0.02% w/v) for the same duration. The remaining quantity was washed with distilled water and used as a control (T_3). 100g of the samples were used for the studies of MAP. The sample was packed in a gas mixture flushed polyethylene bags (GFPE) with 3kPa O_2 + 5kPa CO_2 and a balance of N_2. And another was packed in PET jars equipped with silicone membrane window on the lid and also PE bags, with conditions that of the first one was used. Samples were then analyzed for gas concentrations, color, and microbiological analysis (APHA, 1992) Sensory evaluation of the samples was evaluated for characteristics like taste, aroma, taste, texture, and overall acceptability.

The results revealed that the samples that were subjected for pretreatment and then placed for MAP treatment were highlighted by different physicochemical parameters and also extension in their shelf-life, by a reduction in mean respiration rate, and higher retention of ascorbic acid and firmness. The sample pretreated with citric acid resulted in anti-respiratory activity leading to an extension in shelf life in GFPE, PET, and PE bags. Control samples packed using MA showed an increase in CO_2 buildup. The jackfruit bulbs immediately after separation showed an increased respiration and size reduction, and the pretreatment given to the samples was found beneficial in reducing the degree of respiration at beginning of the MAP storage. The respiration rate of pretreated and control samples packed under different MAP conditions decreased during the storage and the pretreated MAP samples showed a decrease for a longer duration. The firmness of the pretreated bulb was strongly affected by dip pretreatment. Firmness loss in pretreatment samples was in the range of 7-17%, whereas the controls showed a significantly greater reduction in firmness, ranging from 20-30%. Samples stored in GFPE bags showed significantly higher firmness compared to passive MAP up to 35 days of storage, whereas PE bags showed maximum softening of the fruits. The restriction in firmness loss could be attributed due to stabilized respiration, which in fact restricted the enzymatic hydrolysis of cell wall components in pretreated samples under different MAP storage.

The Ripening Index of control samples was higher compared to the pretreated samples, from day 7 of storage. The addition of citric acid caused a decrease in the pH values and increased titratable acidity against control samples.

There was also a significant change in the color of the samples. GFPE bags with pre-treated samples showed no significant changes in values up to 21 days of storage; but on the other hand, the same samples decreased significantly from the 7th day for control samples. Samples stored using GFPE bags showed significantly better color for both control and pre-treated samples due to the low levels of O_2 (L*= 51.44, C*= 21.66).

The samples pre-treated with sodium benzoate and citric acid showed better control compared to those treated without any antimicrobial agents. Gas flushing also helped better control over the count in silicone membrane incorporated PET and PE bags. The low O_2 and high CO_2 restricted the SPC to mold and yeast.

In terms of sensory scores, the dip pre-treated samples showed a delayed decrease in sensory characteristics and overall acceptability. Those stored under the atmosphere of 3kPa O_2 + 5kPa CO_2 had better maintenance of flavor, color, and texture than those kept in PE and PET bags with silicone membrane windows. Higher O_2 and CO_2 in PE and PET bags with Silicone membrane windows caused brown discolorations on the samples.

Avocados

In the study done by Forero, (2007), a silicon membrane system was used to study the storage of avocado (*Persea americana* Mill. Var. Hass). This was performed in a small sealed experimental chamber fitted with a silicone membrane. The areas of the membrane were calculated so as to achieve 3% oxygen and 30, 50, and 70% reduction of the respiration rate due to the effect of the modified atmosphere on the products' metabolic activity. The fruit stored at regular atmosphere (control) and in a silicone membrane were kept at a temperature of 7°C and 90% RH. The gas concentration was analyzed using gas chromatography. The ripening was measured at 15°C and respiration rate at 7°C respectively. The effect of sulphur dioxide treatment in the silicone membrane system was also analyzed.

The fruits that were stored under a membrane system designed for 30 and 50% reductions showed a similar trend; a reduction in CO_2 concentration and O_2 accumulation for the first few days. Chambers with a small window area of 28cm^2 stabilized the O_2 concentration at 2.5% and 3.45% of CO_2 in 6 days and these had a significant effect on the quality of the fruits. The fruits were better in terms of color retention and overall appearance when compared with the fruits stored under different MA conditions. The chambers with medium window areas exhibited gas stability up to 15 days, and those with large window areas stabilized the gas up to 24 days. The respiration rate of the fruits stored in chambers with medium and large membrane areas showed an increased respiration rate and ripens rapidly. The treatment of sulphur dioxide was independent of the size of the membrane and did not show any significant effect on the color of fruits, but those that were untreated became opaque compared to the smaller membrane sizes. Non-treated fruit stored in chambers with medium and large membrane areas turned purple after the storage period but remained relatively firm. It was also noticed that the firmness was independent of the size of the membrane and sulphur dioxide treatment. There was reduced/no damage in fruits stored under the membrane, they had better appearance, firmness, aroma, and flavor, reduced chilling injury, and found marketable, but on the other hand those kept as control and those stored at 7°C in chambers with large membrane areas were extensively damaged. This could be attributed to increased oxygen availability in the chamber. Fruits that were treated with SO_2 and stored in chambers with smaller membrane areas developed a uniform distinctive purple coloration after six days of ripening and were firmer requiring an additional four-day period for proper softening.

Tomatoes

Tomatoes are considered "protective foods" because of their high nutritive value and are widely used in Indian culinary preparations. Tomato is the 2nd largest produced vegetable crop after potato and sweet potato and is the most common vegetable to be preserved by canning (TNAU Agritech Portal, 2015). Tomatoes are highly perishable and have a very short shelf life. Deterioration normally is caused by natural ripening process, water loss, physical damage, microbial spoilage, etc and most of these are temperature dependent. Hence, it is necessary to be stored in proper temperature conditions to enhance its shelf life. Tomatoes (varieties 'Co-1', 'Co-3' and 'PKM-1') were harvested and packaged within 4-6 h after harvest. The fruits were kept in ambient condition (30±3°C; 60% RH) and also at 10±2°C with 85% RH. The time taken for 35% of spoilage was noted and expressed as the number of shelf-life days. HDPE bottles were used for storage and lids of the bottles were fitted with silicone membrane which consisted of fine nylon fabric (52 to 54 g/m^2) covered with a thin and uniform layer (about 90 microns; 80 g/m^2) of silicone rubber compound, as described by Raghavan et al. (1982). The composition of gas was analyzed using gas chromatography. Skin and flesh thickness, firmness, pH, ascorbic acid, acidity, and β-carotene were analyzed as per AOAC (1990). Reducing sugar, non-reducing sugar, and total sugar were also evaluated.

The firmness of the PKM-1 variety was highest during the day of harvest and the lowest was in the Co-1 variety on the day of storage under MA at ambient temperature (28±3°C). The highest acidity was observed in the PKM-1 variety on the 14th and 21st day of storage at ambient and low storage, respectively. The lowest acidity of Co-1 was recorded on the 63rd day of storage under ambient conditions and the 70th day of storage under low temperature. The lowest acidity for the same was observed on 77th days of storage at low temperatures. The TSS content increased with increasing storage period in both the storage conditions. The highest values of TSS and reducing sugar were recorded for the Co-3 variety on the 77th day of storage at low temperatures. The highest value for non-reducing sugar was observed for Co-1 variety on the 77th day of storage at low temperature and the highest total sugar content was observed for Co-3 on the 77th day of storage at low temperature (10±2°C). Both lycopene and β-carotene content increased with increasing period of storage. The highest lycopene was recorded on the 63rd day of storage in Co-1 variety under ambient storage conditions. The highest β-carotene content was recorded in Co-1 variety on the 70th day of storage under low-temperature storage. The longer shelf-life PKM-1 variety had higher skin and flesh thickness and higher firmness when compared to the other varieties (Co-1 and Co-3, respectively). PKM-1 tomatoes stored at low temperature showed the highest shelf-life of 88 days at 5% CO_2 whereas the lowest shelf-life of 37 days was observed in the Co-1 variety at 12% CO_2.

For those stored at ambient conditions, the highest shelf-life of 71 days was observed in the PKM-1 variety at 5 % CO_2 whereas the lowest shelf-life of 31 days was observed in the Co-1 variety at 12 % CO_2. (Ravindra & Kailappan, 2007). From this experiment, it was understood that the best method of treatment for extending the shelf life of the tomatoes was the low temperature (10±2°C) with 5% CO_2 since it gave better firmness, color, etc. and this will also depend upon the variety of tomato chosen for the treatment.

Advantages & Disadvantages of Silicone Membrane Systems

Silicone rubber is physiologically inert, odorless, non-corrosion, non-toxic, anti-clotting, good compatibility and also can withstand harsh conditions. Silicone membrane is heat resistant; that means it has the capability to withstand temperatures upto 305°C and low temperatures even at -100°C. It is very hygienic, as it is resistant to microbial buildup, and used in food and beverage applications. It does not dissolve in organic solvents, but is adversely affected when strong acids are used. The disadvantages include its poor tear strength, cost and compatibility, since there are environments and applications were they perform poorly. It hardens when heated in air and loses its elongation as it deteriorates. (Bricout, 1996; Vercauteren et al., 2021).

CONCLUSION

The use of silicone membrane technology could be prevailed as an alternative or in combination with controlled atmospheric, for extended storage of fruits and vegetables. The SMS system allows the diffusion of gases, at different rates, which is dependent considerably on its physical and chemical properties. The fruits and vegetables because of their water content and nutrient-rich, require special provisions for their storage, and storing them using this technology, will help in enhancing better qualities than those stored at normal conditions and also helped in increasing the shelf-life. The efficiency of the membrane is dependent upon selective membrane permeability and product respiration rate. Though the laboratory experiments were done to know the extension of shelf life provided by these systems. Further research was done not only to determine the shelf-life extension but also its characteristic effect on taste, color, respiration rate, firmness, etc. But some of the fruits and vegetables required additional pretreatments in order to avoid adverse effects during the storage period. Currently, research is being carried out on the feasibility of silicone membrane systems in the storage of fruits, vegetables, and other food materials so that they could be used on a large scale for commercial storage. This technology is being used as a processing and separation method in the food industry such as deionizing cheese whey, etc. and as a technique to extend shelf-life It is now used on a small laboratory scale due to its high capital expenditure on construction and maintenance as well as challenges involved in controlling the atmosphere of storage of fruits and vegetables. This could be commercialized by adopting standardized techniques for the extended shelf-life of produces with minimal nutrient losses.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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