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ORIGINAL PAPER

Effects of Minimal Processing Technologies on Jackfruit (*Artocarpus heterophyllus* Lam.) Quality Parameters

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Abstract

Jackfruit (*Artocarpus heterophyllus* Lam.) is a tropical fruit with high nutritional value and reported health benefits, but its commercialization is hindered by its mass (> 10 kg) and difficulty to peel. Jackfruit bulbs (JFBs) are often sold fresh, washed only with water and packaged in polypropylene containers, which minimizes their shelf life and makes it necessary to consume them shortly after purchase. Minimally processed products (MPPs) are ready-to-eat fresh-cut products, and the technologies used to produce them to allow better utilizing fruits, extending their shelf life and freshness as much as possible. This review describes reported advantages and limitations that minimal processing methods exert on JFBs. These methods include low temperatures, anti-browning agents, anti-respiratory substances, texturizing agents, controlled atmospheres, edible coatings, osmotic agents, preservatives, and UV treatments among others. Their effects on physiological and physicochemical parameters, as well as effects on shelf life and sensory attributes are also discussed. Evidence shows that minimal processing techniques are a viable option that can be used on JFBs, which preserve quality and sensory attributes by reducing metabolic reactions like respiration rate (RR) and ethylene production. Shelf life can be extended up to 50 days without changes in sensory attributes, and higher retention of bioactive compounds in comparison with untreated JFBs, but results vary with each specific treatment. Minimal processing technologies are a rapid, efficient, and reliable alternative that retain quality and extend the shelf life of fresh JFBs. With further improvements in preservation and standardization, the commercialization of jackfruit could be brought to bear.

Keywords Jackfruit · Minimal processing methods · Shelf life · Quality

Introduction

Jackfruit (*Artocarpus heterophyllus* Lam.) is part of the *Moraceae* family, and different varieties are known. It is native to India, but also grows in other tropical and subtropical climates around the world. The fruit is oval-shaped and spiny, but its most distinguishing feature is its mass, typically 10–30 kg (Haque et al. 2015), which is considered the world largest fruit (Peng et al. 2013). The pulp is golden-yellow, and is arranged in fleshy bulbs (30–35% of the fruit's weight), each containing a single seed (Swami et al. 2014). Jackfruit bulbs (JFBs) are edible, and can be described as slightly acidic, creamy, smooth, fibrous, sweet, and highly fragrant, similar to other tropical fruits like banana or pineapple (Prakash et al. 2009). They are rich in sugars, mainly sucrose, fructose and glucose (Ong et al. 2006; Rahman et al. 1999), minerals, dietary fiber, carboxylic acids, and vitamins. Jackfruit crops are economically important for most countries that cultivate them. JFBs can be consumed fresh as ingredient in salads, or processed into fruit bars, cakes, jams, ice cream, chutney, jelly, juices, nectars, and fermented beverages among others (Fernandes et al. 2011; Asquieri et al. 2008). However, according to the FAO (2010), jackfruit has great potential for commercialization as minimally processed fruit, due to its size and difficulty to peel. This review summarizes the effects of using minimal processing methods on JFBs, specifically on physiological and physicochemical parameters,

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shelf life, and sensory attributes. This work can serve to promote the consumption of jackfruit in countries outside of its region of cultivation.

Economic Importance

Jackfruit is commercially cultivated in India, Thailand, Indonesia, Philippines, Malaysia, Bangladesh, southern China, Australia, Florida (USA), the Caribbean, and Latin America (APAARI 2012; Jagadeesh et al. 2007). A mature jackfruit tree produces up to 700 fruits per year, or 50–80 ton/ha (APAARI 2012). For example, Bangladesh produced 1.40 million tons of jackfruit in 2013 (Mondal et al. 2013), corresponding to 0.42–0.50 million tons of edible bulbs. As it is cultivated in more regions, the economic importance of jackfruit has significantly increased. In particular, Mexican jackfruit production increased by 200% in the last 10 years, reaching an approximate production value of USD3.7 million (SIAP 2015).

Nutritional Content

Table 1 shows the nutritional composition of JFBs. From this data, it can be seen that JFBs have a high water content (70–80%), where carbohydrates are the major macronutrients ranging from 13 to 25% [sucrose (4.46 g/100 g), fructose (1.26 g/100 g), and glucose (0.96 g/100 g)], followed by proteins (0.6–1.5%) and lipids (< 1%) (TACO 2006; Ong et al. 2006). They are considered a good source of dietary fiber (Shafiq et al. 2017; Sharma et al. 2015), have low energy content (88 kcal/100 g of edible portion) and are highly digestible (TACO 2006). Its micronutrient profile includes vitamins and minerals (Sharma et al. 2015; Peng et al. 2013; TACO 2006). Phytosterols (β-sitosterol, lanosterol, stigmasterol, and campesterol), essential fatty acids (linoleic acid and linolenic acid), and essential amino acids (valine, leucine, and lysine) have also been reported (Sharma et al. 2015; Peng et al. 2013).

Regarding its phytochemical profile, Singh et al. (2015) reported that JFBs contain phenolic acids (gallic acid, ferulic acid, and tannic acid), whose concentration can increase (gallic acid) or decrease (ferulic acid) during ripening. Other authors have also found flavonoid compounds, specifically, catechin, rutin, and myricetin (Sharma et al. 2015). de Faria et al. (2009) showed that the main carotenoids are *all-trans*-lutein (24–44%), *all-trans*-β-carotene (24–30%), *all-trans*-neoxanthin (4–19%), *9-cis*-neoxanthin (4–9%), and *9-cis*-violaxanthin (4–10%). Resveratrol has also been detected and quantified (0.07 μg/g dry weight) in jackfruit pulp (Shrikanta et al. 2015). The phytochemical profile of jackfruit suggests that its consumption may promote a good health.

Table 1 Nutritional composition of jackfruit bulbs (JFBs) as reported by different sources

Variable	Shafiq et al.(2017)	Goswami et al. (2011)	Taco (2006)
Energy (kcal)	ND	ND	88
Moisture (%)	71.60	79–83	76
Ash (%)	1.89	0.7–1.1	0.8
Total protein (%)	1.48	0.6–1.0	1.4
Total fat (%)	0.63	ND	0.3
Available carbohydrates (%)	13.08	13–18	22.5
Fiber (%)	*6.32	0.5–1.0	*2.4
Starch (%)	ND	7–8	ND
Vitamin C (mg/100 g)	22.47	5–8	14
Thiamine (mg/100 g)	ND	ND	0.10
Riboflavin (mg/100 g)	ND	ND	0.04
Pyridoxine (mg/100 g)	ND	ND	0.05
Niacin (mg/100 g)	ND	ND	Tr
Total polyphenols (mg GAE/100 g)	240	ND	ND
Carotenes (μg/100 g)	ND	330–520	ND
Potassium (mg/100 g)	ND	ND	234
Sodium (mg/100 g)	ND	ND	2
Calcium (mg/100 g)	ND	ND	11
Iron (mg/100 g)	ND	ND	0.58
Phosphorus (mg/100 g)	ND	ND	14

Data is presented per 100 g (fresh weight) of edible portion

ND not determined, *Tr* traces, *GAE* gallic acid equivalent

*Total dietary fiber

Because of its bioactivity, some authors have proposed that JFBs can be used as ingredients for the development of functional foods (Shafiq et al. 2017; Jagtap et al. 2010; Chandrika et al. 2005), but more research is still required.

Postharvest Ripening

Jackfruit is a highly perishable climacteric fruit with a short postharvest life, during which important changes in color, texture, and taste occur (Singh et al. 2015; Fernandes et al. 2011; Ong et al. 2006). According to Saxena et al. (2011), jackfruit must be harvested without causing mechanical damage; but also, the fruit can be harvested immature or ripe. In the case of ripe fruits, the quality important parameters are total soluble solids (20–30 ° Brix) and titratable acidity (0.19–0.50 g/L of malic acid). In this point, a characteristic aroma of jackfruit can be detected. Some important physiological and physicochemical parameters of ripe jackfruit are shown in Table 2, but it should be mentioned that its optimum ripening stage and quality criteria during harvesting have not been clearly defined (Saha et al. 2016).

Color can be an indicator of consumption stage, for example, an unripe JFB is white-yellow, while a ripe bulb is orange-yellow. Total sugar content and soluble solids-to-acids ratio are responsible for the sweet taste of JFBs (Saha et al. 2016). Jagadeesh et al. (2017) reported that higher firmness correlates with lower acidity, suggesting that these variables may be related to harvest index; and they concluded that in immature state, the jackfruit has higher firmness and acidity versus maturity stage of the fruit.

Jackfruit has a high respiration rate (RR) that ranges from 20 to 25 mg CO_2/kg h (Saxena et al. 2008). RR reflects metabolic activity and plays a major role in the postharvest life of raw fruits and vegetables (USDA 2016). With respect to jack fruit, RR and ethylene production are also inversely associated with its shelf life. However, when the skin has a lesion or a physical damage, fungi and bacteria can enter, causing to a rapid decay and an increase of water loss. In this point, the RR may also increase, and consequently, an increase in ethylene production decreasing shelf life (Vargas-Torres et al. 2017; Saxena et al. 2008; Latifah et al. 2000).

According to Saxena et al. (2011), the storage of whole fruit is usually carried out at 12 °C and the packaged bulbs are stored at 5–6 °C. They mentioned that the whole fruit is more susceptible to chilling injury (dark-brown discoloration of the skin and increase susceptibility to decay) than the bulbs (pulp browning). Other important postharvest problems in whole jackfruit include immature or overripe fruit and non-uniform ripening within the fruit (especially in for large sized fruits), infestation with fruit boring pests (softening of infected area), and spoilage by inadequate storage temperature among others. These postharvest disorders may affect the quality of minimal processing JFBs as discussed in further segments.

Technological Uses

JFBs are usually consumed fresh, due to their excellent organoleptic attributes. It can also be used as an ingredient that can be added to numerous foods and beverages like juices, nectars, purees, jams, concentrates, wines, and others. According

Table 2 Physiological, physicochemical and physical properties of ripe jackfruit bulbs (JFBs) and some physiological disorders of jackfruit

Parameter	Value	Reference
Respiration rate at 20 °C (mg CO_2/kg h)	20–25	Saxena et al. (2008)
Ethylene production (ppm)	0.6–0.7	Saxena et al. (2008)
Total soluble solids (TSS, °Brix)	20–35	Souza et al. (2011); Ong et al. (2006)
pH	4.8–5.8	Souza et al. (2011); Ong et al. (2006)
TSS:acid ratio	54–134	Jagadeesh et al. (2007)
Specific heat (kJ/kg °C)	2.70–3.92	Souza et al. (2011)
Thermal diffusivity (°C m^2/s)	5–85	Souza et al. (2011)
Density (kg/m^3)	1020	Souza et al. (2011)
Hue	83–87	Vargas-Torres et al. (2017)
Firmness (N)	45	Saxena et al. (2008)
Chilling injury (CI)		
Jackfruit	10–12 °C	Saxena et al. (2011)
JFBs	< 5 °C	Sally et al. (2011)
JFBs CI symptom's	Pulp browning and poor flavor	Saxena et al. (2011)
Misshapen fruits	–	Saxena et al. (2011)
Immature or overripe fruit	Non-uniform ripening within the fruit	Saxena et al. (2011)

to Swami et al. (2012), jackfruit pulp can be used to make low-sugar jams (Table 1).

Asquieri et al. (2008) fermented jackfruit and obtained a product with similar characteristics to those of table wine (*demi–sec*), such as an ethanol content of 13°GL (Gay-Lussac). Subjects, who consumed the beverage, reported that they found it acceptable. Furthermore, Kumoro et al. (2012) investigated the effect of yeast (*Saccharomyces cerevisiae*) and initial sugar (14% *w*/*w*) concentrations on jackfruit juice wine fermentation. They reported that using 0.5% (*w*/*v*) yeast and the fermentation of the juice for 9 days is the best manner to produce a good wine with 12% of ethanol and a particular jackfruit aroma. Subsequent studies suggested that the jackfruit juice is optimal for wine making (Sharma et al. 2013; Baidya et al. 2016). Also, jackfruit pulp can be mixed with other tropical fruits to prepare functional drinks (Chakraborty et al. 2011) with high content of bioactive compounds, such as phenolic compounds (gallic acid, ferulic acid, and tannic acid), flavonoid compounds (catechin, rutin, and myricetin), and carotenoid compounds (β-carotene, α-carotene) among others (Singh et al. 2015; Sharma et al. 2015; de Faria et al. 2009).

Wong and Tan (2017) analyzed the production of spray-dried honey jackfruit powder from enzyme-liquefied puree. They obtained good powder quality in terms of water activity, solubility, moisture content, hygroscopicity, color, and bulk density, and mentioned that jackfruit powder could be potentially incorporated into various food products. Other authors have incorporated soy lecithin and gum arabic to enhance the viscosity of jackfruit powder (Pua et al. 2007). The use of jackfruit powder in products like fruit bars have shown good sensory acceptance by judges (Manimegalai et al. 2001).

Molla et al. (2008) studied a technique to prepare jackfruit chips. Jackfruit slices were fried in palm oil at 170 °C for 10 min, until a yellowish color was obtained. When consumed by a panel of judges, results showed good sensory acceptance. Jackfruit can also be dehydrated to produce snacks (Yi et al. 2016b; Rohitha-Prasantha and Amunogoda 2013; Swami et al. 2012).

Jackfruit is unique because each of its parts (pulp, peel, and seed) is utilizable. For example, Tulyathan et al. (2002) analyzed the physicochemical and rheological properties of jackfruit seed flour and starch. They reported good water and oil absorption capacity and high protein content (9% dry weight). Odoemelam (2005) studied the effect of the heat (roasted at 120 °C for 2 h) on the functional properties of jackfruit seed flour. They reported that water and oil absorption increased in the heat flour compared to raw flour; also, gelation concentration and bulk density were enhanced by the heat treatment compared to raw flour. The authors also mentioned that jackfruit seed flour (raw or heat) may be used as a partial substitute in baked goods to reduce their gluten concentration, suggesting its possible use as a functional ingredient in food systems.

Jackfruit seed starch can be used to make biodegradable films (Ferreira-Santana et al. 2018). Others showed that jackfruit shell powder is a good source of natural antioxidants and other bioactive compounds, with potential uses in the pharmaceutical and food industries (Sharma et al. 2015). Singh et al. (2015) reported the presence of tannic, gallic, ferulic, and caffeic acids in jackfruit skin and seeds, and highlight the importance of these compounds in human health.

The value-added products that can be obtained from jackfruit are a good alternative for its commercialization beyond food applications. Nevertheless, its main use remains as fresh fruit that can be consumed by modern health-conscious consumers; for this reason, we will focus on the minimal processing methods applied for JFBs conservation.

Jackfruits as Minimally Processed Products (MPPs)

Ripe jackfruit can be sold whole, alternatively, bulbs can be packaged ready-to-eat in polyethylene bags or polypropylene containers, but they have a limited shelf life from 3 to 15 days (Vargas-Torres et al. 2017; Farheen et al. 2016; Wong and Tan 2017; Adiani et al. 2014). Adequate processing methods are important to maintain quality, freshness, and stability (microbial and enzymatic) during storage (Ekanayaka et al. 2015), lack of proper knowledge during harvest, transport, and storage leads to high amounts (> 30%) of jackfruit being discarded as waste every year by producers and the food industry (Swami et al. 2014; Mondal et al. 2013).

Minimally processed products (MPPs) are defined as a fruit or vegetable, or any combination that has been physically altered from its original form, but remains in a fresh state. MPPs have also been referred to as fresh-cut, lightly processed, fresh processed, partially processed, or preprepared products (IFPA 2002). Their freshness, health benefits, and convenience has resulted in an increased demand for various products (Ramli et al. 2017), and in particular, jackfruit and other tropical fruits (FAO 2010). MPPs shelf life varies from 3 to 15 days, depending on the product, packaging, and storage conditions; and the latter must be product-specific in order to maximize it (Farheen et al. 2016; Adiani et al. 2014). Development of suitable processing protocols for minimally processed jackfruit bulbs (MP-JFBs) could overcome problems related to decreased quality (flavor loss, tissue softening, cut-surface browning, etc.) (Saxena et al. 2012a). A proposed diagram for MP-JFBs is shown in Fig. 1, based on the information discussed throughout this work.

Methods for MP-JFBs preservation include (alone or combined) low temperatures, anti-browning agents, anti-respiratory substances, texturizing agents, controlled atmospheres, edible coatings, osmotic agents, preservatives, and others. These treatments reduce RR and other metabolic reactions that can result in decreased quality (USDA 2016). For example, Tao et al. (2013) suggested that enzymatic browning

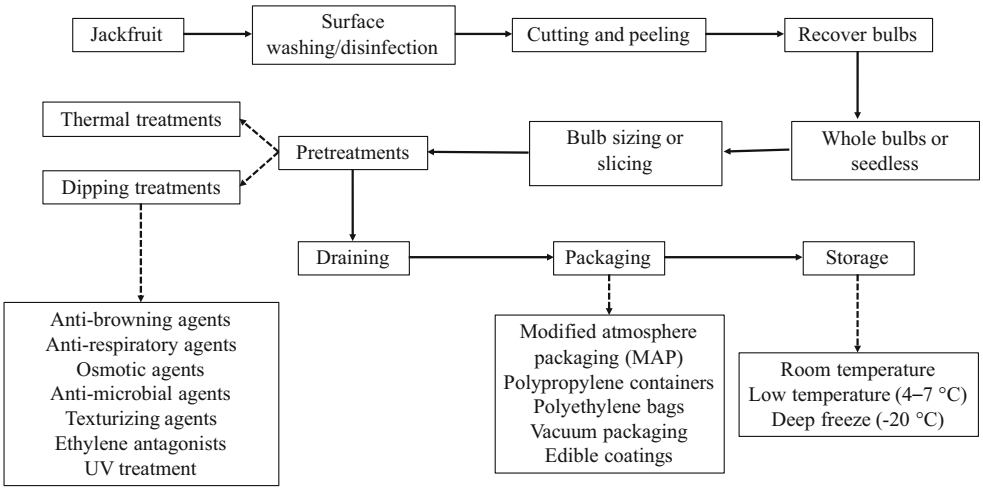

Fig. 1 Suggested flow chart to prepare minimally processed jackfruit bulbs (MP-JFBs) or slices (Vargas-Torres et al. 2017; Farheen et al. 2016; Swami et al. 2014; Saxena et al. 2012a)

of MP-JFBs is catalyzed by polyphenol oxidase (PPO), and therefore, inhibiting its activity could preserve color and overall appearance.

MPPs can be sources of potential bacterial outbreaks if they proliferate during storage. *Erwinia aphidicola* and *Bacillus subtilis* have been reported in MP-JFBs (Ekanayaka et al. 2015), both of them considered human pathogens. Proper treatments on raw materials, postharvest operations, sanitation in the processing plant, and control of final products can maintain the organoleptic qualities and safety of jackfruit.

Table 3 summarizes the effects of different treatments used on MP-JFBs that are discussed in the following paragraphs.

Storage Temperature

An adequate storage temperature can maximize the postharvest life of any fruit, or it can otherwise induce undesired color, texture, and physical changes (Souza et al. 2011). Jackfruits and other tropical fruits are particularly sensitive to low temperatures and can develop chilling injuries (Mortuza et al. 2014). Ong et al. (2006) reported changes in pH, color, and flavor during jackfruit ripening when stored at 28 °C and 70–75% relative humidity. Furthermore, consuming untreated JFBs after 3 days of storage (4 °C) could be a health risk for the consumer by the possible presence of bacterial pathogens included: *Escherichia coli*, *Salmonella spp*., *Listeria monocytogenes*, *Erwinia aphidicola*, and *Bacillus subtilis* among others (Ekanayaka et al. 2015; Adiani et al. 2014). The low temperature storage decreases the enzymatic activity and slows down biochemical changes. Latifah et al. (2000) evaluate the influence of storage temperature (25, 10, and 2 °C) on the quality of MP-JFBs. They found that storage at mild-high temperatures (10 or 25 °C) significantly increases RR and weight loss, but these were significantly lower at 2 °C. They also found an increase in pH, a decrease in total soluble solids (TSS), and minimal changes in color after 7 days of storage at 2 °C. The authors discussed that temperature management is key for preserving freshness and quality of MP-JFBs, and mentioned that the optimal temperature for MPPs differs for whole/intact fruits.

Dipping Treatments

Dipping fruits and vegetables in aqueous solutions of osmotic, anti-browning, anti-respiratory, anti-microbial, preservative, and texturizing agents are widely used on MPPs (Sutar and Sutar 2014). Anti-browning agents or thermal blanching as pretreatment can mitigate enzymatic browning (Saxena et al. 2015; Xu et al. 2015). For example, decreasing (< 4.5) or increasing (> 8) pH can prevent enzymatic browning by inhibiting PPO activity in JFBs (Tao et al. 2013). In addition, ascorbic acid (10 mM) was effective in complete inhibition of jackfruit PPO compared to malic and citric acids at the same concentration, which showed an increase in the activity of PPO (27 and 33%, respectively), presumably due to inadequate concentration of these acids. According to the authors, the reasons of the activation-acceleration of jackfruit PPO in presence of citric and malic acid are not clear. On the other hand, ascorbic acid is capable of reducing *O*-quinones to diphenols to prevent the pigment formation by affectation of the active center of PPO due to a reduction of Cu^{+2} to Cu^{+}; but also, ascorbic acid reacts with the histidine residues at the active site to inhibit the PPO activity.

The effects of citric acid and ascorbic acid on the shelf life of vacuum-packed jackfruit cubes stored at 4 °C were analyzed by Navindra et al. (2009). The JFBs were cut into cubes (25 mm); the cubes were dipped in the test solutions of citric acid (CA) at 1% and ascorbic acid (AA) at 1% by separately or in a combined solution of CA + AA at 1% for each additive. After they were drained and were placed in laminated polyethylene vacuum bags (80 μm of thickness) and vacuum packaged at 550 mbar atmospheric pressure, then packages were stored at 4 °C for 15 days. The color was negatively affected (increased browning), texture and pH decreased,

Table 3 Effects of different treatments on quality parameters of minimally processed jackfruit bulbs (MP-JFBs)

Treatment	*Experimental conditions	Results	Shelf life (days)	Sensory attributes	Reference
Untreated	Untreated storage at 10 °C	Significant increase in microbial load > 9 and 6.6 log CFU/g in aerobic bacteria, yeasts, and molds	< 3	Samples were not safe to eat	Adiani et al. (2014)
Untreated	Room temperature storage	Changes in pH, TA, TSS, and color	2	Significant changes in quality parameters	Ong et al. (2006)
Low temperature	Storage at 2 °C	Changes in pH, TA, and TSS, weight loss and RR increased	7	Minimal changes in color	Latifah et al. (2000)
Low temperature	Storage at −20 °C	Carotene and vitamin C content decreased gradually. TSS and pH decreased, TA increased	270		Mortuza et al. (2014)
Thermal blanching as pretreatment before freeze-drying	Immersion in water at 80 °C for 1–2 min	> 95% polyphenol oxidase inactivation			Xu et al. (2015)
Dipping in anti-browning agents and vacuum packaging	Pretreatment in 1% ascorbic and citric acid, vacuum packed at 550 mbar in polyethylene pouches and storage at 2–4 °C	Increased TA, decreased pH and texture. Microbial load was minimized	15		Navindra et al. (2009)
Dipping in anti-browning and preservative agents	Dip in potassium sorbate (1.5 g/L), ascorbic and citric acid (10 g/L), packaging in polypropylene boxes, storage at 6 °C	Changes in pH, TA and reducing sugars by effect of treatment, microbial load was minimized	12		Ulloa et al. (2007, 2010)
Immersion in antioxidant and anti-microbial agents	Dip in 1.5% ascorbic acid/2.5% calcium lactate for 2 min, packaging in polyethylene bags, storage at 7–10 °C	Color and TSS were preserved. Microbial load was minimized	5	Minimal changes in color and texture	Acedo et al. (2013)
Immersion in antioxidant and anti-browning agents	Dip in 1.5% citric and ascorbic acid,1% sodium metabisulphite, packed in polystyrene packages and over wrapped with polyvinylchloride stretch film, storage at 4 °C	Increase in firmness. Microbial counts were within safe-to-consume limits	7	Acceptable sensory quality	Ekanayaka et al. (2015)
Immersion in chemical additives and glass jar-packaging	Sucrose (250 g/kg), potassium sorbate (0.5 g/kg), citric acid (1 g/kg), sodium bisulfite (0.25 g/kg), ascorbic acid (0.5 g/kg), and salts (1.5 g/kg) was prepared at 80 °C and placed inside the jar	Color was preserved	120		Ulloa et al. (2007)
Dipping in anti-browning and texturizing agents	Dip in 1% calcium chloride and 0.02% ascorbic acid for 30 min, and storage at 4 °C	Better firmness and color retention in treated samples, as compared to the control	20	Treated samples were preferred over untreated samples	Saxena et al. (2012a)
Vacuum-infused calcium solution	Vacuum-infusion of 1% calcium for 15 min	Firmness and texture were enhanced. Higher retention of ascorbic acid. Color was slightly affected.	14		Ramli et al. (2017)
MAP combined with chemical additives and low temperature	Pretreatment with calcium chloride, ascorbic acid, and sodium benzoate, MAP (3 kPa O_2, 5 kPa CO_2) storage at 4 °C	Decrease RR and ethylene production, preserved firmness, color, and TSS:acids. Microbial load was minimized	35	Slight changes in color, flavor, and consistency. Overall	Saxena et al. (2008)

Table 3 (continued)

Treatment	*Experimental conditions	Results	Shelf life (days)	Sensory attributes	Reference
				acceptability changed	
MAP combined with chemical additives and low temperatures	Pretreatment with citric acid and calcium chloride, packed in polyethylene, polystyrene and polypropylene, storage at 3–5 °C and − 12 °C	Physiological losses were less stored at − 12 °C than at 3–5 °C, ascorbic acid and sensory attributed were slightly affected compared refrigerated and control samples	10–20		Sally et al. (2011)
Dipping in chemical additives prior to MAP and low temperatures	Citric acid dip (0.25%), bagged in polyethylene packages at 80% vacuum, stored at 3–5 °C	Microbial load (mesophilic aerobes, coliforms, yeasts, and molds) was controlled during storage, minimal changes in pH and TSS	18		Farheen et al. (2016)
Thermal blanching as pretreatment before freeze-drying and MAP packaging	Immersion in water at 100 °C for 2 min followed by a quick freezing at − 10 °C for 1 h and drying at 60 °C previous to MAP (low density polyethylene, polypropylene and aluminum laminates pouches) under vacuum	Microbial load (mesophilic aerobes, coliforms, yeasts, and molds) was controlled during storage, minimal changes in sensory attributes in samples packed in aluminum laminates pouches	24		Dhanesh et al. (2018)
Application of edible coatings	*Aloe vera* gel with a commercial gelling agent	Weight loss is minimized. Preserved ascorbic acid, TA, pH, and TSS	7		Teja et al. (2016)
Dipping in anti-browning, texturizing, preservatives, and ethylene antagonist prior to application of edible coatings	Dip in potassium sorbate (1%, 5 min), calcium chloride (0.1%, 5 min), and 1-MCP (0.01%, 5 min) before applying edible coatings (0.8% sodium alginate or 0.7% xanthan gum) and 4 °C storage	Decreased RR and weight loss. Preserved color, TSS, TA, and pH. Lower microbial counts than untreated samples. Higher retention of ascorbic acid and phenolic compounds.	12		Vargas-Torres et al. (2017)
Anti-browning, texturizing, and preservatives. Edible coatings and stored under MAP	Dip in sodium benzoate, calcium chloride, ascorbic acid, and citric acid before chitosan coating and storage in MAP (3 kPa O_2, 6 or 3 kPa CO_2, N_2 balance) at 6 °C	Higher retention of ascorbic acid (83%) and phenolic compounds (95%). Microbial counts were low	50		Saxena et al. (2013)
Ultraviolet pretreatment	UV pretreatment (240 nm, 5 min) before being packaged in polypropylene containers and stored at 5 °C	Higher microbial reduction was obtained after treatment	14		Bizura-Hasida et al. (2013)
Hot air-drying	50, 60, and 70 °C	Color of jackfruit slices was affected, also a carotenoid degradation was observed			Saxena et al. (2012b)
Drying	Hot air-drying, freeze-drying, infrared-drying, microwave-drying, vacuum-drying	A decrease in lightness and a light brown color was observed in the jackfruit chips in all drying methods			Yi et al. (2016b)
Dipping in chemical additives prior to drying process	Osmo-blanching at 30 °Brix using commercial sugar syrup and calcium chloride at 1.5 *w/v* for 2 to 6 min at 85 °C before freeze-drying (− 30 °C for 4 h) and hot-drying (60 °C)	Rehydration of samples exhibited a good sensory attributes	240		Saxena et al. (2015)

Table 3 (continued)

Treatment	*Experimental conditions	Results	Shelf life (days)	Sensory attributes	Reference
Hot drying prior to package in polypropylene, polyvinyl chloride, or laminated aluminum foil	Samples dried at 50 °C and air velocity of 1.6 m s^{-1} for 24 h	Fruit sheet exhibited a good sensory acceptance. Nonetheless, samples packaged in laminated aluminum foil were most stable during storage than the others packaging materials	120		Che Man and Sin (1997)
Immersion in chemical additives prior to osmotic dehydration and in-pack pasteurization)	Pretreatment with 1% citric acid, MPT (65.9 °Brix, 68.5 °C for 180.6 min) and storage at 6 °C	Texture was preserved, 64% carotenoid retention, as compared to control samples	240	Changes in texture and overall acceptability	Saxena et al. (2009b)
Osmotic dehydration	3 h immersion in a 60 °Brix sucrose solution	Increased TSS and TA. Color was minimally affected. Decreased weight	355	Treatment affected flavor	Swami et al. (2014)

MAP modified atmosphere packaging, *RR* respiration rate, *TSS* total soluble solids, *TA* titratable acidity, *1-MCP* 1-methylcyclopropene, *MPT* multitarget preservation techniques (MPT)

*Optimal experimental condition

and titratable acidity (TA) increased during storage of untreated controls. Ascorbic acid and citric acid were effective anti-browning agents but performed better when they were applied individually. They also achieved a 15-day shelf life extension of MP-JFBs with good sensory attributes.

Ulloa et al. (2010) evaluated the effects of a dipping treatment on physicochemical and microbiological quality of JFBs. Samples were dipped for 5 min in an aqueous solution of potassium sorbate (1.5 g/L), citric acid (10 g/L), and ascorbic acid (10 g/L). After treatment, samples were packed in polypropylene boxes and stored at 6 °C. Treatment maintained quality parameters (pH, TA, water activity, color, and TSS) during 12 days of storage. Microbial counts were relatively low (10^1 to 10^3 CFU/g) in treated samples. These results are similar to a previous study by the same group, where sodium bisulfite, ascorbic acid, and sodium ascorbate stabilized the color of JFBs for 120 days (Ulloa et al. 2007).

Acedo et al. (2013) dipped JFBs for 2 min in an aqueous solution of ascorbic acid (1.5%) or calcium lactate (2.5%) as anti-microbial agent, samples were dipped by separately, packaged in sterile resealable polyethylene bags (50-μm thick), and stored them at 7–10 °C. After 5 days of storage, calcium lactate treatment reduced microbial (aerobic bacteria, coliform, yeast, and molds) load by 85–99%, without changes in color, TSS, and sensory quality, as compared to the untreated control. Furthermore, similar results in color, TSS, and sensory quality were observed between samples treated with calcium lactate and ascorbic acid; however, the anti-microbial effect of ascorbic acid was lower (76–89%) than calcium lactate. The anti-microbial effect of calcium lactate has been attributed to their ability to uncouple microbial transport processes (Saftner et al. 2003). The same study showed that these results (regarding microbial load) were comparable to those obtained when the samples were immersed in a 150-ppm chlorine solution for 3 h; however, chlorine negatively affected sensory quality, particularly taste.

Browning, changes in firmness, sensory properties, and microbiological quality of MP-JFBs were analyzed during storage (up to 7 days) at 5–7 °C (Ekanayaka et al. 2015). Samples were dipped in different pretreatment solutions (0.5% sodium metabisulphite, 1% sodium metabisulphite, 1.5% citric acid, 1.5% ascorbic acid, 3% citric acid, or 3% ascorbic acid) for 5 min, packaged in polystyrene and wrapped with polyvinylchloride (PVC) stretch film before storage. All samples retained color and showed minimal browning, in particular when ascorbic acid was applied. These results are similar to those reported by Tao et al. (2013). Microbial counts were within safe-to-consume range and coliforms were not detected in any samples, while no significant changes in color, aroma, or taste were evident after 7 days at 5–7 °C storage.

Saxena et al. (2012a) used response surface methodology to optimize minimal processing operations on firmness,

browning index, color, and overall acceptability of JFBs. They studied the effects of calcium chloride (0.13–1.47%) and ascorbic acid (0.005–0.030%) concentration and exposure time (8–43 min). The authors found that 1% calcium chloride, 0.020% ascorbic acid, and 30 min of treatment time were optimum conditions that minimized browning and maximized firmness, color, and overall acceptability after 20 days of low temperature storage.

Ramli et al. (2017) evaluated the effects of dipping JFBs in a 1% calcium chloride solution (1%), at 8 °C by two different methods: immersion (18 h) and vacuum-infusion (15 min). Immersion method promoted softening after 3 days of storage, while firmness was maintained in vacuum-infused samples for up to 14 days of storage. The authors suggested that the removal of intracellular gases in the tissue by vacuum treatment could facilitate the penetration of calcium, and consequently, promote the formation of calcium pectate gels that strengthen the cell walls. Vacuum-treated samples also retained more ascorbic acid (92%) compared to immersed (63%) and untreated (16%) samples. A slight browning was detected in all treated samples after 14 days of storage.

According to the literature (Ekanayaka et al. 2015; Saxena et al. 2009a, 2015; Ulloa et al. 2007, 2010; Ramli et al. 2017; Acedo et al. 2015), anti-browning (sodium bisulphite, sodium metabisulphite, citric acid and ascorbic acid), anti-microbial (citric acid, ascorbic acid, potassium sorbate, calcium lactate and chlorine), and texturizing agents (calcium lactate and calcium chloride) are adequate options to use on JFBs. Some treatments perform better when individually used, while others are better when used in combination (Navindra et al. 2009). It should also be considered that some additives, packaging, and storage temperature, all affect sensory quality of MP-JFBs.

Modified Atmosphere Packaging (MAP)

Reducing atmospheric O_2 and increasing CO_2 can extend the postharvest life of MPPs, due to a decreased RR and overall metabolism. This can mitigate the reported sevenfold RR increase that happens during minimal process operations (peeling, cutting, etc.), which may occur due to increased surface area exposed to the atmosphere, and to increased metabolic activity of injured cells (Rivera-López et al. 2005).

MPPs are normally packaged in film bags to reduce RR. Passive atmosphere modification inside the container may retard browning, spoilage, and maintain a fresh appearance (González-Aguilar et al. 2000). In some cases, modified atmosphere packaging (MAP) and low temperature did not extend JFBs shelf life because of excessive physiological and mechanical stress suffered during processing. Nonetheless, a pretreatment, such as those previously discussed, may be used together with MAP (Martínez-Ferrer et al. 2002).

Saxena et al. (2008) analyzed the effects of different MAP methodologies to extend the shelf life of JFBs stored at low temperatures. MP-JFBs at ripening stage (without visual physical alterations) were pretreated with calcium chloride, ascorbic acid, and sodium benzoate, and subsequently stored on either polyethylene bags or polyethylene terephthalate (PET) jars with 3 kPa O_2 and 5 kPa CO_2, or polyethylene bags with air and stored at 4–6 °C. Samples were divided in two groups for pretreatment: the first group was dipped in a solution that contained calcium chloride (1% *w*/*v*), ascorbic acid (0.02% *w*/*v*), citric acid (1% *w*/*v*), and sodium benzoate (0.045% *w*/*v*) for 30 min, while the second group was dipped in a solution with calcium chloride (1% *w*/*v*) and ascorbic acid (0.02% *w*/*v*) for 30 min. JFBs increased their RR immediately after being separated from the whole fruit (70 mg CO_2/kg h), but a decrease in cut-induced RR was observed (23.5 mg CO_2/kg h) when low temperatures and pretreatments (in both pretreatments) were applied, in particular in the first pretreatment. In addition, a greater decrease in RR and low ethylene production were observed in MAP bags. Firmness decreased by 7–17% in pretreated samples, as compared to untreated samples, which showed the highest losses (20–30%). In general, browning was delayed, color was preserved, and pretreatments controlled microbial growth. They found no changes in sensory attributes like flavor and texture after 35 days of storage at 4 °C in samples packaged polyethylene bags. On the other hand, the panelists reported changes to their overall acceptability in samples packaged in PET jars, which may have been related to an anaerobic fermentation process.

Using the same experimental conditions described, Saxena et al. (2009a) evaluated phytochemical changes in MAP-stored JFBs. They reported a lower loss of total phenolics (7%), flavonoids (8%), carotenoids (43%), and ascorbic acid (31%) in treated samples as compared to the control (26, 33, 57, and 49%, respectively) after 35 days of storage at 6 °C. They also mentioned a decreased enzymatic browning index and color preservation.

Additionally, Sally et al. (2011) investigated the influence of different dip pretreatment (citric acid and calcium chloride at 0.5% *w*/*v* concentration, applied separately) and different packaging (polyethylene, polypropylene, and polystyrene) on the postharvest shelf life of minimally processed JFBs stored in refrigeration (3–5 °C) and deep-freeze temperature (−12 °C). The authors informed that samples treated with citric acid, packed in polyethylene bags, and stored in deep-freeze temperature showed less physiological losses in weight and ascorbic acid, but also, minimal changes in sensory attributes were detected compared to refrigerated samples. Furthermore, the extension shelf life of refrigerated samples were 10 to 12 days, while under deep-freeze samples were 18 to 20 days.

Latifah et al. (2000) suggested that when MAP is used, it is necessary to consider condensed humidity on the film, which is influenced by temperature oscillations during storage and

handling, which could promote physical (weight loss and color), chemical (pH, total soluble solids, and total sugars), and biochemical (respiration rate and ethylene production) changes in MP-JFBs, reducing their physicochemical quality.

Farheen et al. (2016) evaluated the effect of vacuum percentage (60, 70, and 80%) when storing MP-JFBs under MAP. Samples were pretreated in a solution that contained an anti-respiratory agent (citric acid at 0.25% *w*/*v*), packaged in polyethylene bags (thin-layer sheet 2 mm), and stored at low temperature (3–5 °C) for 3 weeks or frozen (− 12 °C) for 6 weeks. Low temperature and freezing at 80% vacuum controlled microbial load (< 1 log CFU/g), with minimal pH changes (5.75 and 5.83, respectively) after storage, as compared to the control (5.91 and 5.87, respectively). In contrast, reported a decrease in vitamin C and carotene content in deep-frozen (− 20 °C) JFBs by Mortuza et al. (2014).

Recently, Dhanesh et al. (2018) evaluated the effect of blanching process (100 °C for 2 min) followed by a quick freezing (− 10 °C for 1 h) previous to drying (60 °C) and packaging in three different materials (low density polyethylene, polypropylene, and aluminum laminates) under vacuum. Samples packed in aluminum laminates pouches had the better results without significant changes in sensory attributes and microbiological stable for 24 days.

Various authors have used different treatments on other fruits. For example, anti-browning agents (1% ascorbic acid and 0.5% chamomile aqueous extract) and heat treatments (55 °C for 45 s) prior to MAP (100% CO_2) extended the shelf life of fresh-cut lotus root for 21 days at 5 °C (Son et al. 2015); it has been reported that chamomile extracts contain a series of flavonoid compounds (myrecitin, quercetin, and kaempferol), which exhibited a good antioxidant activity (Moraes-de-Souza et al. 2009). Calcium chloride, citric acid, and MAP (5% O_2, 10% CO_2, 85% N_2) preserved fresh-cut papaya cubes for 25 days at 5 °C, without significant changes in quality parameters (Waghmare and Annapure 2013). These results were found in other fruits could be used to develop additional preservation methods that can be used for MP-JFBs. MAP has been shown to retard physiological and physicochemical reactions, delay growth of spoilage microorganisms, and maintain fresh appearance of MP-JFBs. MAP treatments are also compatible with other preservation methods like immersion in chemical additives and low temperatures, which may provide an additive effect to prevent the loss of bioactive compounds and quality during storage.

Edible Coatings

Edible films and coatings can be applied to minimally processed fruits, with the goal of increasing their shelf life. They provide a barrier that decreases metabolic processes (RR and ethylene production), prevent dehydration, and delay senescence due to the generation of a low O_2/high CO_2 microclimate (Antunes et al. 2012). They are also compatible with anti-microbial or anti-browning agents (Vargas-Torres et al. 2017).

Saxena et al. (2013) used calcium chloride, ascorbic acid, citric acid, and sodium benzoate as pretreatments, before applying a chitosan coating on MP-JFBs. Samples were stored under MAP (3 kPa O_2, 6 or 3 kPa CO_2, and N_2 balance) at 6 °C. The combined treatment minimized losses of total phenolic compounds (5%) and ascorbic acid (17%) after 50 days of storage. Microbial counts (aerobic bacteria, yeasts, and molds) were also low in all samples. Accordingly, the effect of chitosan coating was found to be appropriate to extend their shelf life for up to 50 days, without significant changes in overall acceptability during a sensorial evaluation.

Teja et al. (2016) evaluated the effects of different coatings (pectin and *Aloe vera* gel with a commercial gelling agent) on postharvest quality of MP-JFBs during 7 days of storage at 6 °C. Weight loss was lower (< 7%) when *A. vera* was used, as compared to pectin (10.8%) and control (14%). *A. vera* was found to be a suitable coating that prevents moisture loss, while pectin was not an effective moisture barrier, due to *A. vera* gel contains a variety of polysaccharides, in addition to pectic substances. The authors concluded that the coatings did not affect the nutritional content of MP-JFBs, except for soluble carbohydrates, particularly because the films (edible coatings) typically are polysaccharides-based soluble in water. They also showed that pectin-coated JFBs had a better overall acceptability, but *A. vera*-coated JFBs had better quality parameters during 7 days of storage at 6 °C.

Vargas-Torres et al. (2017) applied edible coatings (xanthan gum, sodium alginate, or gellan gum) combined with 1-methylcyclopropene (1-MCP) to MP-JFBs. Samples were pretreated with ascorbic acid, calcium chloride, and 1-MCP prior to the application of edible coatings. Treated samples showed a decrease ripening and had lower weight loss and RR, as compared to control samples. Quality parameters (color, pH, TSS, TA, and firmness) and bioactive molecules (ascorbic acid and phenolic compounds) were preserved during storage at 5 °C. Treatments increased shelf life up to 12 days without apparent changes in sensory attributes.

Edible coatings are compatible with chemical or natural additives like anti-microbials, antioxidants, texturizing agents, and bioactive compounds. Studies mentioned that edible coatings act as a barrier against O_2 and CO_2, reduce RR and ethylene production, and prevent decay and color changes during storage.

Ultraviolet (UV) Treatments

Ultraviolet (UV) treatments are a non-thermal alternative to chemical sanitization that can be used on fresh-cut products or products that come into contact with food (FDA 2000). Its anti-microbial effect is due to extensive DNA damage that inhibits replication (USDA 2016). Bizura-Hasida et al. (2013) pretreated MP-JFBs with UV radiation (240 nm, 5 min), and

packaged them in polyethylene bags. UV radiation significantly reduced the population of spoilage microorganisms like aerobic bacteria, yeast, and molds (reduction of ≥ 3 log CFU/g). This increased shelf life for 14 days at 5 °C, without exerting significant changes in color or other sensory attributes. The effects of UV radiation have been minimally studied on MP-JFBs, which merits future experiments. UV could also be used with infrared heat (Siddiq et al. 2013) during MP-JFB production.

Drying Treatments

Dry JFBs have a great potential for commercialization (Wong and Tan 2017), which has lead authors to focus on these products. For example, Saxena et al. (2012b) analyzed the effects of hot air-drying (50, 60, and 70 °C) on JFB slices. They found that JFB slices showed carotenoid degradation, a decreased yellow color, and an increase in browning as drying temperature and time increased. Furthermore, Yi et al. (2016b) evaluated the effect of different drying methods (hot air-drying, freeze-drying, infrared-drying, microwave-drying, vacuum-drying) on explosion of puff-dried jackfruit chips. They found that the color of the chips was significantly affected by drying method, specifically, a decrease in lightness and a light brown tonality, which suggested the presence of Maillard reaction products. Also, the color preservation of jackfruit chips can achieve using an instant controlled pressure drop-assisted freeze-drying (Yi et al. 2016a).

Also, Saxena et al. (2015) with the aim to obtain dehydrated and crispness JFBs investigated the effects of pretreatments and a combination of freeze-drying and hot air-drying protocols. After pretreatment samples (osmo-blanching at 30° Brix using commercial sugar syrup and calcium chloride at 1.5 *w/v* for 2–6 min at 85 °C), they were drained and subjected to a combined freeze-drying conditions (− 30 °C for 3–4 h, to a moisture level of 4–6%, dehydration was carried out by maintaining the chamber pressure at 100–300 Pa and plate temperature at 50 °C for 24 h) and hot air-drying (samples were dried in a Kilburn crossflow cabinet hot air dryer set at 60 °C with 2 m s^{-1} air velocity) process. The dried crisp product obtained from various drying schedules was evaluated for rehydration characteristics, shrinkage, textural properties, color values, and overall acceptability. Samples treated by a combined-drying process resulted in an extension shelf life of 8 months under ambient conditions (25–27 °C) with good sensory attributes, in particular crispness.

Che Man and Sin (1997) studied the stability of prepared thin-layer sheet (2 mm) based jackfruit puree (55%), glucose syrup (15%), sugar (25%), and water (5%); the sheets were then placed into a cabinet dryer (dried at 50 °C and air velocity of 1.6 m s^{-1} for 24 h). Lately, the sheets were packaged in different packaging material (polypropylene, polyvinyl chloride, and laminated aluminum foil), and reported that fruit sheet was most stable when packaged in laminated aluminum foil during storage (3 months), and had good sensory acceptance.

In addition, Saxena et al. (2009b) investigated the effects of an osmotic dehydration technique [osmotic solution (55–75 °Brix), temperature (50–70 °C), and time (150–180 min)] used on JFBs. Samples were initially treated with citric acid to acidify them. Treated samples had maximum water loss, while minimizing changes in TSS, and without changes in microstructure. Carotenoids were also retained (64%) under experimental conditions of 65.9 °Brix, 68.5 °C, 180.6 min, and storage at 6 °C. They achieved a shelf life of 240 days, but also reported negative changes in flavor and texture after storage. Swami et al. (2014) also used an osmotic treatment on MP-JFBs. Samples were dipped in a sucrose solution (40 or 60 °Brix) for 3 h. Treated samples (60 °Brix) had increased TSS and TA, while color was minimally affected as compared to control. Furthermore, a decreased bulb weight was attributed to water loss due to the sucrose solution. These treatments increased their shelf life up to 12 months. Furthermore, a sensory evaluation showed that dipped samples at 60 °Brix were preferred.

Conclusion

Minimal processing methods can be a viable option to use on jackfruit bulbs. They can preserve and enhance quality parameters like texture, firmness, and color, while slowing ripening rate due to decreased respiration and ethylene production. Combined pretreatments like dipping in anti-browning, anti-respiratory, osmotic, anti-microbial, texturizing, edible coatings, and ethylene antagonist solutions are options that have shown significant results. Pretreated samples can then be packaged in polypropylene containers, polyethylene bags, or vacuum packages with modified atmospheres. Combinations of pretreatments and low temperature storage could synergistically extend their shelf life from 5 up to 50 days with minimal or no changes in sensory attributes. Additional experiments are required to improve processing conditions and standardize the use of pretreatments on jackfruit and jackfruit bulbs.

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