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Effects of temperature on postharvest respiratory parameters and quality attributes of ackee (*Blighia sapida* Köenig) fruit arils during storage

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Abstract

The effect of temperatures on the rate of O_2 uptake (*RRO2*) and CO_2 production (*RRCO2*), the Q_{10} and activation energy (Ea) of respiration, the respiratory quotient (*RQ*), the rate of ethylene production, the colour and visual quality attributes of ackee (*Blighia sapida* Köenig) fruit arils "cheese" variety were measured. *RRO2* averaged 0.26, 0.63, and 0.96 mmol kg^{-1} h^{-1} and *RRCO2* averaged 0.22, 0.55, 0.90 mmol kg^{-1} h^{-1} and ethylene production averaged, 47.5, 50.2 and 51.9 nmol kg^{-1} h^{-1} at 5, 15 and 25°C, respectively. Neither *RRO2* nor *RRCO2* correlated with ethylene production. The *RQ* of arils varied from 0.89 to 1.0 and the Q_{10} varied from 1.8 to 2.0, while the Ea ranged from 40.4 to 51.6 kJ $mole^{-1}$. Decay and quality loss were rapid at temperatures above 15°C. When kept under chilling temperature (3°C for 20 days with or without subsequent removal to 25°C), ackee arils showed severe chilling injury symptoms. Decay was also accelerated by the removal to 25°C. Collectively, the data indicate that ackee fruit aril storage is limited to temperatures between 5°C and 15°C.

Introduction

The ackee (*Blighia sapida* Köenig) belongs to the Sapindaceae and is a native plant of West Africa that was introduced to Jamaica in the 18th century. The fruit is a three-celled fleshy capsule containing three valves and three glossy black seeds. When ripe, the fruit splits longitudinally into three sections to reveal the seeds and the thick yellow flesh of the arils, which form the edible portion of the fruit and has a nutty flavor (Barnett, 1939; Barceloux, 2008).

Ripe ackee arils are widely consumed in the Caribbean and West Africa, are one of the national dishes and considered as one of the national symbols in Jamaica. In Jamaica, two types of ackee are recognized – "cheese" or hard and "butter" or soft. The "cheese" ackee aril is hard, cream colored, and retains its shape when cooked and is the preferred one, while the "butter" ackee aril is soft and yellow, losing its shape easily during cooking.

Respiratory parameters of many fruits and their response to temperature have been the subject of numerous postharvest studies. The data are useful to producers and consumers, and can be employed in studies designed to evaluate or model shelf-life. Recently, Benkeblia (2014) investigated the effects of temperature on the respiration rate, ethylene production, and quality attributes of ackee fruit arils. Benkeblia (2014) found that the respiration rate (*RRCO2*) for fruit stored at 5, 10 and 15°C declined with storage duration and with decreasing temperature. He also found that ethylene production, while decreasing as temperature declined, increased during storage, suggesting no linkage to respiratory activity per se. Apart from this work, no data are available on the respiratory parameters including respiratory quotient (*RQ*) of ackee fruit arils.

The responses of plant tissues to temperatures ranging from 0 to 5°C vary according to the tolerance of the species and are further affected by intrinsic and extrinsic factors (Graham and Patterson, 1982). Although refrigeration is the oldest known and classic technology used for extending the shelf-life and preserve the quality attributes of fresh crops, low temperatures are also known to have negative impacts on tropical crops (Wade, 1979; Paull, 1990,1999). Therefore, a proper storage temperature is needed to extend storage life of fresh crops and maintain the quality attributes of harvested crops. These appropriate temperatures should reduce the respiration rate and slow down the metabolic process, without affecting cellular integrity and causing

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metabolic stresses that lead to chilling injury (Parkin *et al*., 1989). On the other hand, postharvest quality attributes also depend on quality at harvest, and these would influence the shelf-life of perishables during storage (Benkeblia *et al*., 2011).

Damage in response to exposure to low temperatures, referred as chilling injury (CI), is an important issue for the postharvest sector because low temperature is one of the most classic techniques to extend the shelf-life of fresh crops (Lyons, 1973; Wang, 1989; Wang, 1994). In fruits and vegetables, CI symptoms appear in different ways depending on the species and the type of tissue (Jackman *et al*., 1988). Indeed, the rate of symptoms development is temperature dependent. The most common observed symptoms in tropical and subtropical fruit are surface pitting and necrosis, internal browning, skin and flesh discoloration and sensitivity to decay. CI symptoms may develop slowly during the chilling period, but their expression is greatly accelerated once the crops or tissues are transferred to warmer temperatures (i.e., above 20°C) (Jackman *et al*., 1988; Hatton 1990). Different methods are also used to alleviate the severity or symptoms development of CI such as controlling storage conditions (Hatton, 1990; Lurie and Sabehat, 1997), modified atmosphere packaging (Wang and Qi, 1997; Pesis *et al*., 2000), exogenous chemical treatments (Wang *et al*., 2006) as well as genetic manipulation to develop chilling-resistant crops (Fung *et al*., 2004; Sevillano *et al*., 2009).

The objective of this study is to calculate respiratory parameters needed for mathematically describing the respiratory rates for ackee fruit arils as a function of temperature, and to determine the susceptibility of arils to developing chilling injury at low temperatures and the impact of this disorder on some quality attributes of stored arils.

Materials and Methods

Plant materials

The ackee trees, 'cheese' variety, used for this study were grown in the Botanical Garden of the University of the West Indies. The fruits were randomly harvested from three different trees when the capsule was fully open and the samples were pooled. Immediately after harvest, the arils were carefully separated from the husk, placental tissues, and seeds. Removal of the arils can be accomplished without damage when the fruit are ripe, as the red placental membrane is very soft. After their separation and prior to physiological (*RR* and ethylene) assessments, arils were packed in polystyrene boxes for 24 h under each three temperature regimes (5 ± 1°C, 15 ± 1°C and 25 ± 1°C) to permit temperature equilibration. Alternately, fruit were held at 3°C to induce CI and subsequently held at 25°C to permit the expression of symptoms, as described in the section below.

Respiration rates (RR_{O2} and RR_{CO2}) assessment

The respiration rates (RR_{O2} and RR_{CO2}) were determined using a static respirometer method as described by Benkeblia *et al*. (2000). Detached arils (200 ± 10 g) were placed in 1-L glass jars previously equilibrated at the required temperature and stored in temperature-controlled rooms (5 and 15°C) and controlled room temperature (25°C). For each temperature, jars were closed and the gas composition of each jar analysed at seven time points 0, 1, 2, 3, 4, 5, and 6 h to be able to select only those data associated with aerobic respiration as of oxygen is depleted in the jar and CO_2 increases. To also avoid changes in pressure in the jars that can occur following the removal of multiple gas samples, the air sample for composition analysis was circulated through the analyser (model ICA250, International Controlled Atmosphere Ltd Instrument Division, Kent, UK) and back to the chamber. The sampling duration was 2 min. Respiration rates (RR_{O2} and RR_{CO2}) were calculated by fitting O_2 depletion and CO_2 accumulation data for the seven time points with a linear regression and expressed as mmol kg^{-1} h^{-1} O_2 and depletion did not exceed 4% during the holding period. For each respiration measurement, three jars were used and measurements were duplicated.

Ethylene production assessment

Ethylene production was determined by the same method described for the respiration rate but using a different gas analyser (model ICA56, International Controlled Atmosphere Ltd Instrument Division, Kent, UK). Ethylene production was calculated by fitting ethylene accumulation data for the seven time points with a linear regression and expressed as nmol kg^{-1} h^{-1}. For each ethylene measurement, three jars also were used and measurements were duplicated.

RQ, E_a and Q_{10} calculation

The respiratory quotient ($RQ = RR_{CO2}/RR_{O2}$) was determined for fruit at all three temperatures. The Q_{10} was determined by plotting log(RR) against temperature (T): $\text{Log}(RR) = aT + b$. The predicted respiration rate at 0°C (RR_0) was calculated from the b coefficient ($RR_0 = 10^b$) and Q_{10} from the a coefficient ($Q_{10} = 10^{10a}$). Apparent activation energy (Ea) was calculated by Labuza (1980) based on Arrhenius equation, where T = temperature (K), Ea = activation energy (J mol^{-1}) and R = gas constant (8.3 J mol^{-1} K^{-1}).

Chilling injury (CI) assessment

Susceptibility of ackee fruit arils to chilling injury was determined on six different lots of stored arils. For each lot, arils were removed and packed into polystyrene boxes, each containing approximately 250 g. The weight of individual arils ranged from 6.9 to 10.5 g and the average weight per aril was 8.1 ± 0.55 g. The arils were stored for 20 d at 3 ± 0.5°C and 85-90% relative humidity. For three of the lots, symptoms of CI were recorded after 5, 10, 15 and 20 d storage. For the remaining three lots, arils were held at 25°C for 1 to 2 additional days and incidence and severity of CI was recorded. The severity of chilling injury was also expressed as a chilling index (CINX) (Falik *et al*., 2009). The index (CINX) was calculated as follow:

$$CINX = \frac{(AWND \times 0) + (AWMD \times 1)(AWMdD \times 2) + (AWSD \times 3)}{Total\ Number\ of\ arils}$$

where *AWND* = number of arils with no damage, *AWMD* = number of arils with minor damage (less than 10% damaged), *AWMdD* = number of arils with moderate damage (10 to 30% damaged), and *AWSD* = number of arils with severe damage (more than 30% damaged).

Colour assessment of arils during storage

The colour of the arils was measured on the surface of all fruits in each sample lot described previously using a chromameter (Model 400 chromameter, Konica Minolta Sensing Inc., Osaka, Japan) and the data were expressed in *L*, a*, b** values (CIE). The color reading was taken three times for each fruit (once for each section of the husk) at the equatorial region of each fruit and averaged to give a value for each fruit. The values *a** and *b** were used to calculate chroma $(C^* = [a^{*2} + b^{*2}]^{1/2})$, which indicates the intensity or colour saturation, and hue angle (H° = arctangent[b*/a*]), where 0° = red–purple, 90° = yellow, 180° = bluish-green, and 270° = blue (McGuire, 1992).

Quality evaluation of ackee arils

Quality evaluation procedures were performed at room temperature (c.a. 25°C) as described previously (Wright and Kader, 1997; Agar *et al*., 1999). A panel of eight judges (5 men and 3 women) familiar with the appearance of ackee arils scored the visual quality of the stored arils. Quality evaluation of ackee arils was based on a 5-point hedonic scale as described below. Browning, shrivelling, wilting, and dryness were evaluated on a 5-point hedonic scale as follows: 5: no shrivelling evident (0%); 4: minor shrivelling (less than 20%); 3: moderate shrivelling (21% to 40%); 2: high shrivelling (> 40% to 60%); 1: very high shrivelling (> 60%). Gloss, odour, and overall rating were also evaluated on a 5-point hedonic scale as follows: 5: excellent (fresh cut); 4: very good; 3 acceptable; 2: poor; and 1: unusable.

Data analysis

Data were expressed as the means ± SD and analysed statistically by analysis of variance (ANOVA) using SPSS Version 19 statistical software (IBM Corp., Armonk (NY), USA), and statistical significance was determined at the level $P \leq 0.05$,

Results and Discussion

Respiration rates (RR_{CO2} and RR_{O2}) and ethylene production

The respiration rate of ackee arils increased quasi-linearly with temperature from 5 to 25°C (Figures 1A and 1B). For the three measurements made at each temperature, the lowest RR_{CO2} were 0.19, 0.51 and 0.81 mmol kg^{-1} h^{-1} and the highest were 0.24, 0.58 and 0.99 mmol kg^{-1} h^{-1} at 5, 15 and 25°C, respectively. RR_{O2} were similar to those for RR_{CO2}; the lowest of the three measurements made at each temperatures for RR_{O2} were 0.23, 0.58 and 0.89 mmol kg^{-1} h^{-1} and the highest were 0.29, 0.67 and 1.03 mmol kg^{-1} h^{-1} at 5, 15 and 25°C, respectively. Benkeblia (2014) reported data consistent with those described here, reporting freshly harvested ackee having a RR_{CO2} of 0.21, 0.41 and 0.78 mmol kg^{-1} h^{-1} at 5, 10 and 20°C, respectively. In the present study, the respiratory rates for oxygen uptake and CO_2 production both increased approximately four-fold between 5 and 25°C. While the temperature sensitivity of respiration differs between commodities, the data for ackee are rather typical in that the respiratory rate for most fruits and vegetables increases by 2- to 6- fold from 0 to 15°C (Beaudry *et al*., 1992; Cameron *et al*., 1994; Lakakul *et al*., 1999).

Ethylene production by the ackee arils increased with temperature, but the effect of temperature was very weak (Figure 1C). Aril ethylene production averaged 47.9, 50.2 and 51.9 nmol kg^{-1} h^{-1} at 5, 15 and 25°C, respectively. The rate of ethylene production reported by Benkeblia (2014) was also consistent with ours, averaging 47.6 nmol kg^{-1} h^{-1} at 20°C, although temperature sensitivity was higher in the previous study.

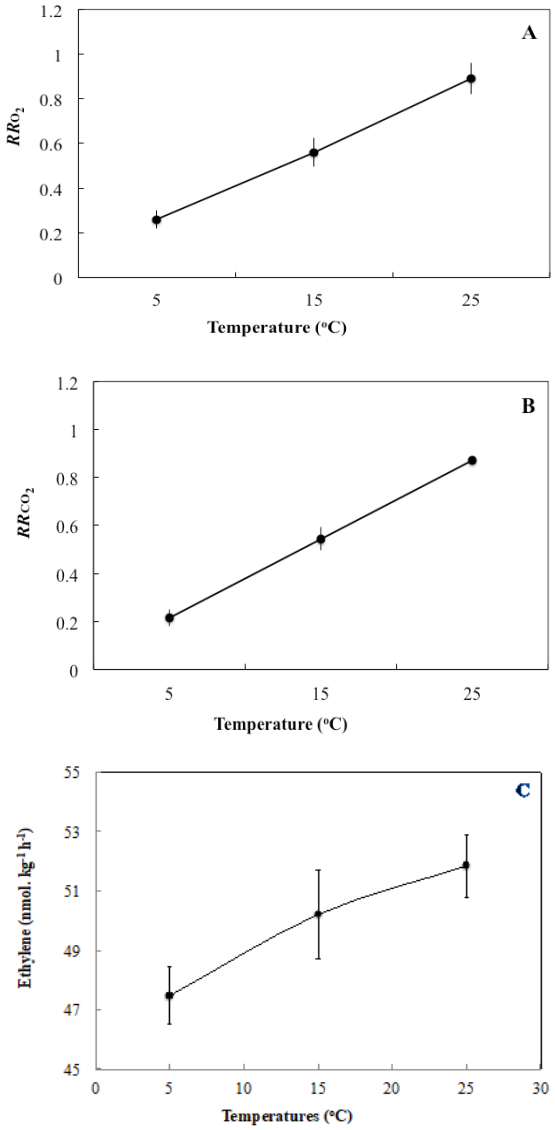

Figure 1. Effect of temperature on the respiration rate, (A): *RRO2*, (B): *RRCO2*, and ethylene production (C) of ackee fruit arils held for one day at the indicated temperatures. Vertical bars indicate SD of n = 6.

RQ, Q_{10} and E_a

Although there is extensive literature on many physiological parameters of fresh crops, there is only one report on a limited number of these parameters in ackee (Benkeblia, 2014). Our data provide the first estimate of the *RQ* of ackee arils. The *RQ* of ackee fruit arils increased with temperature, averaging 0.83, 0.98, and 0.98 at 5, 15 and 25°C, respectively (Table 1). These data are consistent with the findings of previous reported works on other perishable crop species (Platenius, 1942; Hagger *et al*., 1992; Benkeblia *et al*., 2000). Beside temperature and atmosphere composition, other factors influence the *RQ* such as the commodity composition (Platenius 1942) and microbial charge (Benkeblia *et al*., 2000). Although the ackee arils *RQ* was similar to that of many crops, we noticed that the values averaged slightly below. This may reflect oxidation of lipids, which are contained in high levels in arils (Odutuga *et al*., 1992). That lowest *RQ* values were observed at 5°C, suggesting that metabolism is shifted toward lipid degradation at low temperatures. This is consistent with the findings of Eaks and Morris (1956) for cucumber, which has a chilling threshold near 10°C.

The Q_{10} of ackee fruit arils for O_2 and CO_2 respiration rates were 1.81 and 2.01, respectively (Table 1). The corresponding E_a of respiration for ackee fruit arils ranged from 40.4 to 51.6 kJ mole^{-1} and averaged, 41.5 and 47.6 kJ mole^{-1} for O_2 and CO_2, respectively (Table 1). The calculated respiratory rates for O_2 and CO_2 at 0°C (i.e., $RR_{0(O2)}$ and $RR_{0(CO_2)}$) averaged 0.213 and 0.167 mmol kg^{-1} h^{-1}, respectively (Table 1).

Reported Q_{10} values for other crops range from 2.5 to 4.0 between 0 and 10°C, and from 1.5 to 2.0 between 20 and 30°C (Kader, 1987; Cameron *et al*., 1994; Makino *et al*., 1996; Varoquaux *et al*.,

Table 1. Respiratory parameters of ackee fruit arils determined under three temperature regimes

	Temperature	Lowest	Highest	Average
Respiratory quotient (*RQ*)	5	0.83	0.84	0.83
	15	0.97	1	0.98
	25	0.96	0.99	0.98
$RR_{0\,(O2)}$ (mmol kg^{-1} h^{-1})	0	0.175	0.226	0.213
		R^2 =0.98	R^2 =0.98	R^2 =0.98
$RR_{0\,(CO2)}$ (mmol kg^{-1} h^{-1})	0	0.145	0.183	0.167
		R^2 = 0.95	R^2 =0.97	R^2 =0.96
Q_{10}	O_2	1.799	1.91	1.806
	CO_2	1.97	2.07	2.01
Activation energy (E_a)	O_2	40,422	43,567	41,504
(J mole^{-1})	CO_2	46,525	51,594	47,605

1999; Fonseca *et al*., 2002; Nei *et al*., 2005). Like Ea, the value of Q_{10} is also related to the sensitivity of deterioration to temperature, with a higher value portending a more rapid rate of quality decline as temperature increases (Lee *et al*., 1991; Kays 1997; Hertog *et al*., 1998; Kader, 2011).

Despite this interpretation of the utility of Q_{10}, the rate of fresh crop deterioration is not typically first-order against the reciprocal of temperatures (Kruse *et al*., 2011). It well established that the respiration rate does not typically follow a linear trend with temperature due to the complexity of this process, which can be influenced by several intrinsic factors such as maturity stage, variety, internal moisture and type of tissue (Day, 1993; Kruse *et al*., 2011). Although the instantaneous response of plant respiration to temperature change can be approximated by Arrhenius kinetics, to more fully account for a dynamic response, Kruse *et al*. (2011) suggested combining Arrhenius and Michaelis–Menten kinetics.

Colour assessment of arils during cold storage

When ackee arils were kept at the chilling temperature of 3°C, tissues browned as indicated by the decrease in a* and b* values and an increase in hue angle (Table 2). When stored at 3°C and then removed to 25°C, ackee arils browned more than when held at 3°C only. The values of L* decline with storage in a manner similar to that reported by Benkeblia (2014). Benkeblia (2014) noticed that higher storage temperatures did not affect the colour of the arils, and this might indicate that arils do not tolerate temperatures below 5°C, which appears to be detrimental to the quality attributes of this produce. Although not directly comparable, pomegranate arils have also been reported to darken when stored at 5°C for two months (Palma *et al*., 2015) or in modified atmosphere packaging films (Almenar *et al*., 2007; Hussein *et al*., 2015).

Chilling injury (CI) of arils

Ackee arils started showing moderate CI symptoms after 15 days. The CI index was low at 3°C, but moderate at 3°C + 2 days at 25°C (Table 3). After 15 days at 3°C, the CI index was 'moderate' at 3°C, but this transitioned to a 'high' rating after two additional days at 25°C. After 20 days, the CI index was 'high' at 3°C, however it was not determined at 3°C + 2 days at 25°C due to contamination by moulds. These results indicate that ackee arils are sensitive to low temperatures. Based on our results, CI injury was evident after 10 d storage at 3°C, so exposures to this low temperature, if unavoidable during transport and handling, should be kept as short as is practicable.

Although there is extensive literature on CI of subtropical and tropical fruits, this physiological phenomenon is yet to be fully understood. Ackee arils were affected more by CI when transferred to higher temperatures and a rise in respiration and ethylene production was noted. It was reported that ethylene production may influence chilling injury, however, this production does not necessarily initiate this process (Luengwilai and Beckles, 2010). Similarly, storage and transfer from chilling temperatures to warm temperature caused a rise of CO_2 production without a normal corresponding rise in ethylene production (Biale *et al*., 1954). On the other hand, the physiological response of crops to temperature swings is variable. For example, storage of cucumber at low temperature (5, 10 and 15°C) with transfer at warm temperature (25°C) different patterns were noted. Transfer to the warmer temperature after four days storage did show a variation in respiration rate, while transfer after eight or twelve days, *RR* increased sharply (Eaks and Morris, 1956).

Table 2. Colour of ackee fruit arils kept 3°C for up to twenty days with and without removal to 25°C for one (20 d) or two (0 - 15 d) days. Values of the same column with different superscripts are significantly different at $P \leq 0.05$.

	*L**	*a**	*b**	*a*/b**	*C**	*H°*
Storage period (days)			3°C			
0	68.32^{a}	9.93^{a}	59.61^{a}	0.16^{a}	60.43^{a}	-3.48^{a}
5	66.45^{a}	9.41^{a}	51.76^{b}	0.18^{a}	52.61^{b}	-1.01^{b}
10	61.73^{b}	8.74^{b}	52.18^{b}	0.16^{a}	52.91^{b}	-3.09^{a}
15	56.76^{c}	7.08^{c}	43.68^{b}	0.14^{a}	51.17^{b}	0.83^{b}
20	54.36^{c}	6.18^{c}	35.61^{c}	0.17^{a}	36.14^{c}	-1.74^{c}
			3°C + 1 to 2 d at 25°C			
0	68.32^{a}	9.93^{a}	59.61^{a}	0.16^{a}	60.43^{a}	-3.48^{a}
5	59.45^{b}	8.03^{b}	43.53^{b}	0.18^{a}	44.26^{b}	-0.86^{b}
10	48.36^{c}	7.01^{c}	29.25^{a}	0.24^{a}	30.08^{a}	0.59^{b}
15*	n.d	n.d	n.d	n.d	n.d	n.d
20*	nd	n.d	n.d	n.d	n.d	n.d

* colour data could not be accurately determined due to the presence of moulds.

Table 3. Sensory and quality indices of ackee fruit arils kept 3°C for twenty days with and without post-storage holding at 25°C

Temperature	3°C				3°C + 1 to 2 d at 25°C			
Storage (days)	5	10	15	20	5	10	15	20
CINX	1	1	2	3*	1	2	3	*
Browning	5	4	3	1*	4	3	2*	*
Shrivelling	3	3	2	1*	4	2	2*	*
Wilting	5	4	3	2*	3	2*	1*	*
Dryness	5	4	3	1*	3	1*	1*	*
Gloss	5	3	2	1*	3	2*	1*	1*
Odour	4	3	2	1*	2	2	1**	1**
Decay	5	5	3	3	2	2	1	1
Visual quality	4.5	3	2	1	3.5	1.5	1	1
Overall Rating	5	3	2	1	3	2	1	1

Chilling index (CINX): [(no. fruit with no damage *0) + (no. with minor damage * 1) + (no. with moderate damage * 2) + (no. with severe damage * 3)]/total fruit

Visual quality: 5: excellent, freshly cut; 4: very good; 3: good, limit of marketability; 2: fair, limit of usability; and 1: poor, unusable.

Browning, shrivelling, wilting, and dryness: 5: no incidence; 4: minor incidence; 3: moderate incidence; 2: high incidence; 1: very high.

Gloss, odour, and overall rating: 5: excellent; 4: very good; 3: acceptable; 2: poor; 1: unusable

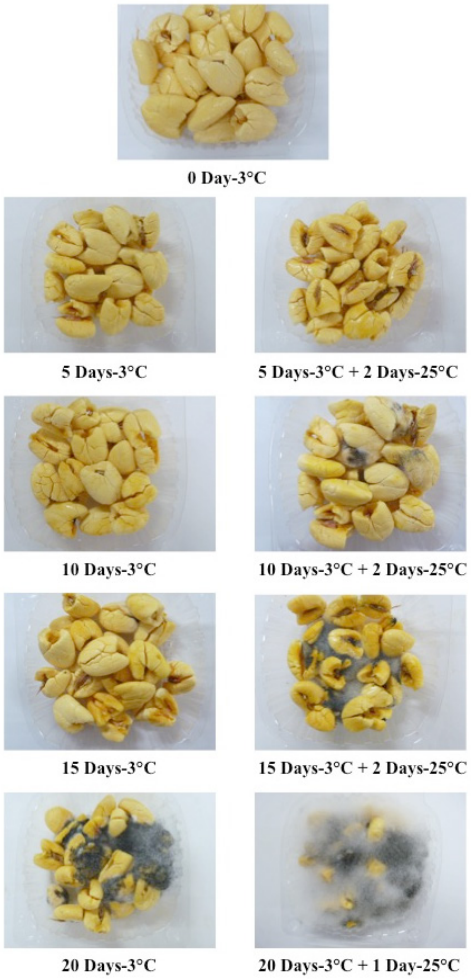

Figure 2. Representative images of arils of ackee fruits stored at 3 °C for up to twenty days (20) with or without transfer to 25 °C for 1 or two days. Arils in these images were not used for analyses.

Effects of chilling temperature on stored ackee arils quality

Aril quality was acceptable after five days storage at 3°C. After an additional 2 d at 25°C (room temperature), the quality declined, but the arils were still acceptable commercially. After 10 days at 3°C, the arils were still considered marketable, while at 3°C + 2 days at 25°C, the quality was poor and the arils started to decay (Table 3 and Figure 2). After 15 days at 3°C, the arils were of poor quality but still no moulds observed, while at 3°C + 2 days the arils were severely infected by moulds and off-flavours were detected. After twenty days, under both conditions (3°C and 3°C + 2 days at 25°C) ackee arils were already decaying, although the decay at 3°C + 1 day was more invasive after one day only (Table 3 and Figure 2).

Conclusion

From the results, it is shown that the respiratory rate of ackee fruit arils is sensitive to temperature. The arils, unprotected by a skin and damaged slightly by the removal of the seed and placental tissues, have a very short shelf-life. Chilling injury was noted within 10 days when holding at 3°C, so higher storage temperatures are suggested. Post-storage removal to high temperature following chilling temperatures accelerated decay and tissue breakdown. Results showed that ackee arils do not tolerate very low or very high temperatures, and storage at intermediate temperatures may be optimal. Additional work describing the response of ackee arils to O_2 and CO_2 would be pertinent for the development of models

appropriate for modified atmosphere packaging to extend further the shelf-life of ackee fruit arils. To this end, the temperature responses for RR_{O2} and RR_{CO2} in terms of *RQ*, Ea and Q_{10} provide needed data. Lacking is the determination of the apparent Km as a function of temperature to enable the creation of temperature-sensitive predictive models for package design (Cameron *et al*., 1994).

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