

# Growth, maturation and ripening of breadfruit, *Artocarpus altilis* (Park.) Fosb.

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## Abstract

Fruit growth of a seedless, 'white flesh' cultivar of breadfruit [*Artocarpus altilis* (Park.) Fosb.] was single sigmoidal as measured by diameter, but double sigmoidal when assessed as dry or fresh weight. The first phase of growth was characterised by size generation while the second phase involved major increase in dry weight, mainly in the form of starch accumulation. The fruit required 13–21 weeks to reach full size from the time when the female inflorescence was first detectable in the terminal leaf sheath though sensory tests of cooked fruit revealed that only fruit 15–19 weeks old was acceptable. This age range coincided with maturity indices such as the appearance of white latex on the fruit skin and flattening of the fruit segments and the spur at the centre of these. Skin colour could not be reliably used as a maturity index. Mature fruit produced a monophasic respiratory climacteric, with CO<sub>2</sub> production reaching 200 ml kg<sup>-1</sup> h<sup>-1</sup> at 25–30°C. In contrast, peak ethylene production was low (1.5 µl kg<sup>-1</sup> h<sup>-1</sup>). The respiratory climacteric of fruit harvested at the earliest maturity (13-to-15-week-old fruit) tended to be higher and later than that of fully mature (19-to-21-week-old) fruit. © 1998 Elsevier Science B.V. All rights reserved

*Keywords:* *Artocarpus altilis*; Breadfruit; Fruit growth; Maturity; Ripening

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## 1. Introduction

Breadfruit, *Artocarpus altilis* (Park.) Fosb., a native of the Indo-Malayan Archipelago and New Guinea, is commonly cultivated throughout the islands of

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the Caribbean. Commercially, it is the most important of the three domesticated species of *Artocarpus*, a genus of over 50 species (Coenen and Barrau, 1961; Barrau, 1976). In the Pacific, there are hundreds of breadfruit cultivars which are grown for food (Ragone, 1989) but only a few of these were introduced to the Caribbean by Bligh in his famous voyage (Powell, 1977) and no more than four or five cultivars are commonly recognised in the Caribbean today (Leakey, 1977; Andrews, 1991).

Breadfruit is consumed unripe and cooked as a starchy staple, equalling or surpassing other tropical crops like sweet potato and cassava in protein and carbohydrate content (Graham and De Bravo, 1981). The fruit has a high post-harvest respiration rate (Biale and Barcus, 1970) but information about its development and maturation is limited. An understanding of the process of fruit development and the identification of suitable maturity indices are important prerequisites for rational development and exploitation of this crop. This study was undertaken to (a) characterise fruit growth patterns and (b) identify possible maturity indices, especially in view of the breadfruit's growing importance as an export crop of the Caribbean (Andrews, 1991).

## 2. Materials and methods

### 2.1. Plant material

Fruit development was studied during November 1989 through May 1990 using nine breadfruit [*Artocarpus altilis* (Park.) Fosb.] trees of unknown age, in backyard orchards in St. Michael and St. James, Barbados. The fruit were of the seedless, 'white flesh' (uncooked flesh colour) cultivar, most common in Barbados and which has been identified on the basis of photographs and herbarium specimens as approximating the Pacific cultivar 'Rare' (D. Ragone, pers. comm.). Young fruit were located by palpation of the terminal leaf sheaths which enclose the female inflorescences, fruit 0.5–1.0 cm in diameter being tagged as the earliest detectable stage (week 0).

### 2.2. Fruit growth and development

About 200 fruit at the earliest detectable stage were tagged, labelled, and monitored over a 5-month period. Separate replicates were monitored weekly on the tree for polar and equatorial diameter, polygon size, and colour of fruit skin [by comparison with Munsell 5GY Color Chart (glossy), Munsell Color, Baltimore, USA]. Polygon diameter was measured from replicas of the fruit surface using a dental impression material (Reprosil; L.D. Caulk Division, Dentsply Intl. Milford, USA) either by direct measurement or by counting the

numbers of entire polygons occurring in a 10 cm<sup>2</sup> area. Dry and fresh weights were measured from fortnightly harvests of six fruit, the dry weight being determined on half fruit dried in an oven at 100–120°C for 3 days. For chlorophyll measurements, six replicate samples, each of 10 skin discs (trimmed of excess non-epidermal tissue), were prepared from frozen fruit of known age using a 7 mm diameter cork borer. Discs were ground in a mortar and pestle using 80% (v/v) aqueous acetone, centrifuged, and assayed for chlorophyll in the supernatant by absorbance at 647 and 664 nm (Porra et al., 1989). Alcohol insoluble solids (AIS) were prepared by homogenising fruit flesh (2 g) in 85% ethanol (5 ml) using a Polytron (Brinkmann Instruments, Westbury, NY, USA) and centrifuging (1000 g, 10 min). The resulting pellet of AIS was washed with 85% ethanol, air-dried and stored at –20°C until analysed. For each fruit stage, four replicate AIS samples (2 mg) were each boiled in 2 ml H<sub>2</sub>O to solubilise starch, and 20 units of amyloglucosidase (ex *Rhizopus niveus*; Seikagaku Kogyo, Tokyo, Japan) in 200 µl of 0.5 M sodium acetate buffer, pH 4.8, 0.01% (w/v) NaN<sub>3</sub> were added to each cooled tube. The samples were incubated in a shaking water bath at 45°C for 24 h, boiled for 5 min to stop the reaction and the resulting reducing sugars assayed using dinitrosalicylate reagent (Miller, 1959). A standard curve using standard weights of starch, hydrolysed enzymatically under identical conditions to the AIS, was prepared and absorbance values converted to mg starch. Aqueous extracts of fruit flesh were prepared and assayed for reducing and total sugars by reaction of the extracts and hydrolysed (1.2 N HCl, 30 min, 100°C) extracts respectively with dinitrosalicylate reagent (Miller, 1959).

### 2.3. Sensory analysis

Replicates of six freshly harvested breadfruit of ages 11, 13, 15, 17, 19 and 21 weeks were cooked just prior to the test. This involved peeling the fruit and cooking portions of each in boiling water without salt or additives for a standard time. Samples (about 20 g each) labelled with a coded tag attached to a toothpick were presented to an untrained taste panel of 13 judges who rated the samples according to the sensory characteristics and scale given in the legend to Table 1.

### 2.4. Post-harvest changes

Tagged fruit of known age were harvested in triplicate from the same tree at an early mature (13–15 weeks old) or mature (19–21 weeks old) stage, weighed, washed and allowed to air-dry before use. Individual fruit were placed in 25 l plastic bell-jars at room temperature (25–30°C) and ventilated with humidified air (1.5 l min<sup>-1</sup>), the exit flow entering a 225-MK3 infra-red gas analyser (ADC, Hoddesdon, UK) via a WA-161 multi-channel switching unit (ADC, Hoddesdon, UK). Linkage to a microcomputer allowed automatic half-hourly data logging.

Table 1

Sensory testing of quality characteristics of cooked breadfruit of 6 different ages to ascertain the best maturity stage(s) for consumption

Fruit age (weeks)	Palatability	Maturity	Flavour	Sweetness	Texture	Discoloration
11	1.54	1.82	2.44	1.29	6.54	2.53
13	1.42	1.97	2.47	1.03	5.17	4.14
15	2.99	3.46	4.22	1.74	5.11	6.83
17	4.00	5.19	4.92	2.97	3.99	7.89
19	6.75	6.57	6.67	2.67	4.08	8.72
21	5.53	6.94	6.36	3.12	3.93	8.28

Key Score	Palatability	Maturity	Flavour	Sweetness	Texture	Discoloration
1	Inedible	Very immature	Strong off flavour	Not sweet	Too soft	Extremely discoloured
3	Just edible	Slightly immature	Slight off flavour	Slightly sweet	Slightly soft	Very discoloured
5	Good	Just mature	Just pleasant	Sweet	Firm	Slightly discoloured
7	Very good	Mature	Pleasant	Very sweet	Too firm	Very slightly discoloured
9	Excellent	Over mature	Very pleasant	Extremely sweet	Much too firm	Not discoloured

Data were statistically analysed using ANOVA.

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Ethylene production was monitored for the same fruit by injecting a 1 ml air sample from the exit air stream into a Photovac gas chromatograph (Photovac, Ont., Canada). Both instruments were calibrated with appropriate certified standards (Matheson Gas Products, NJ, USA). Fruit were simultaneously assessed subjectively by finger pressure for softening using a 3-point scale: '1' represented incompressible fruit, '2' represented spongy (reversibly compressible) fruit and '3' represented fully soft fruit (showing permanent deformation on being compressed). From a parallel batch of mature fruit, replicates of four fruit were removed daily and 10 g flesh samples excised and assayed for starch, reducing sugars and non-reducing sugars as described above.

### 3. Results

#### 3.1. Fruit growth

Polar and equatorial diameters of breadfruit were measured over a 21-week time course. Fruit growth measured in this way displayed a single sigmoidal

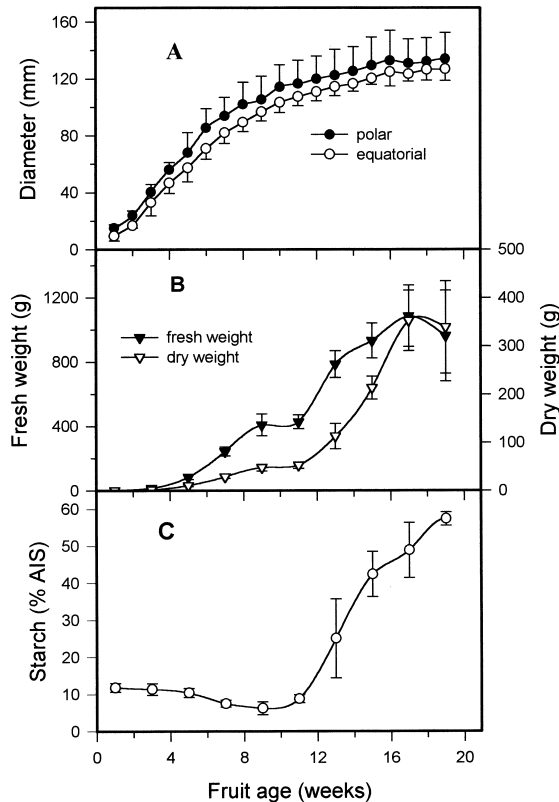


Fig. 1. (A). Growth of breadfruit as monitored by increasing diameter (mean of 15 fruit  $\pm$  SD). (B). Growth of breadfruit as determined by fresh and dry weight (mean of 15 fruit  $\pm$  SD). Starch accumulation in developing breadfruit expressed as % alcohol-insoluble solids (AIS) (mean of 4 fruit  $\pm$  SD).

curve (Fig. 1(A)) and reached a maximum at a fruit age of 14–15 weeks. However, when weight was monitored (Fig. 1(B)), both fresh and dry weight lagged behind diameter increase and both displayed double sigmoidal growth kinetics. The first growth phase took ca. 9 weeks (Fig. 1(B)), followed by an intervening ‘resting’ phase of about 2 weeks and finally the major period of fresh and dry weight increase ensued. Fruit development therefore seemed to occur in two phases: the first concerned with size generation, the second with increase in dry matter.

Breadfruit is a compound fruit (syncarp) formed from the connation of several ovaries fusing from different flowers with individual constituent carpels persisting as polygons on the surface of the developing fruit. At the centre of each polygon the styler remnant persists as a tiny spike which gradually disappears as the fruit segments expand and the fruit matures (Fig. 2). With increasing maturity,

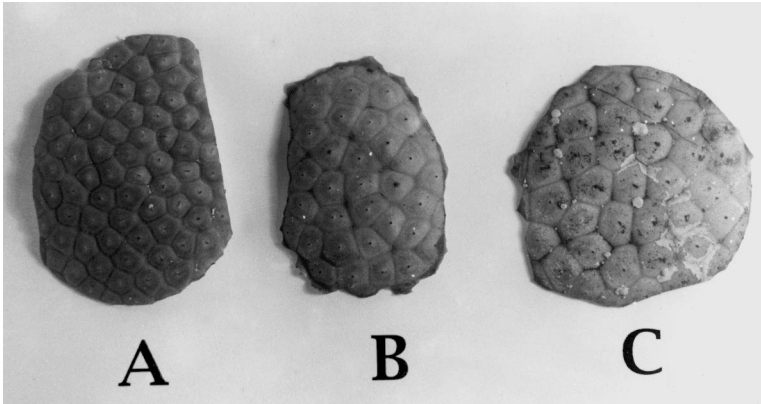


Fig. 2. Peel topography of immature (A), early mature (B) and mature (C) breadfruit. Magnification  $\times 1$ .

the mean number of polygons per  $\text{cm}^2$  reached a minimum at 10 weeks, while actual measurement of polygon diameter showed that polygons did not reach full size until 16 weeks (Fig. 3). The expansion and flattening of the polygons, along with decreased prominence of the spike at the centre of each, gave the skin a relatively smooth, flattened appearance and feel at maturity (Fig. 2). It was also observed that at a fruit age of 15–16 weeks, natural flow of latex commenced from the fruit surface so that the fruit skin became studded with small, congealed rivulets of latex.

### 3.2. Colour changes

Chlorophyll concentrations in the fruit skin were initially low, but increased to a maximum midway through development, finally falling off as full maturation

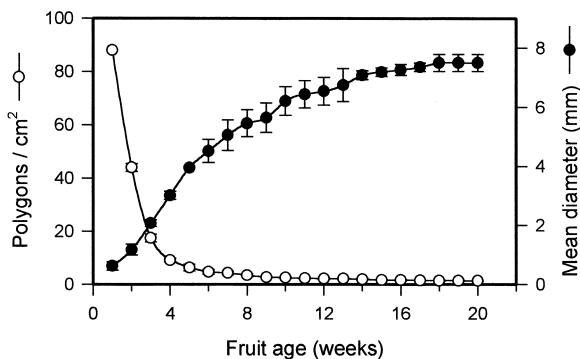


Fig. 3. Size of polygonal peel segments throughout fruit development as measured by mean polygon diameter and number of entire polygons per  $\text{cm}^2$  (mean of 6 fruit  $\pm$  SD).

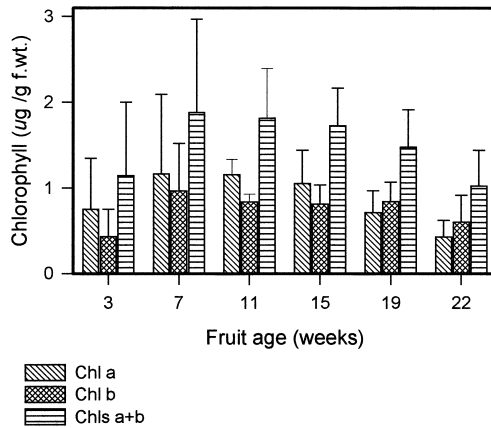


Fig. 4. Chlorophyll concentration in the peel of breadfruit during development (mean of 6 replicates  $\pm$  SD).

approached (Fig. 4). This matched our observations that skin colour was initially light (Munsell Colour Chart 5GY: 8/4), darkened during early maturity (5GY: 6/8 and 5/6) and finally paled to a light green (5GY: 6/8 and 7/8). None of the chlorophyll components, however, gave significant ( $p > 0.05$ ) correlation with increasing maturity.

### 3.3. Carbohydrate changes

Starch content remained low for the first 11 weeks of fruit growth (Fig. 1(B)), but subsequently showed a dramatic rise in the second growth phase, attaining approximately 60% dry weight in mature fruit. Both reducing sugars and total sugars were relatively high during the first few weeks of development but decreased markedly in 8-week-old fruit and remained low as the fruit matured with a slight increase in week 20 (Fig. 5). During the final stages of development the total sugars significantly exceeded reducing sugars.

### 3.4. Sensory analysis of developing fruit

Sensory analyses (Table 1) revealed that panellists detected no differences in palatability, maturity, and flavour between 11- and 13-week-old fruit, but indicated that these sensory characteristics improved in the more mature, 15- through 21-week-old fruit. The younger the fruit the more unacceptable they were with respect to discoloration of the cooked flesh. Only fruit in the 15–19 week age range were deemed acceptable. All characteristics showed a highly significant correlation ( $p < 0.001$ ) with increasing age, with the maturity rating

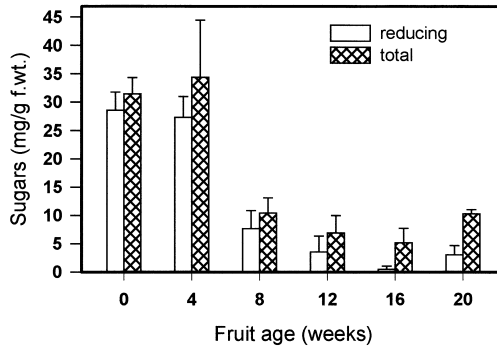


Fig. 5. Quantities of reducing sugars and total sugars in the flesh of breadfruit during development (mean of 4 replicates  $\pm$  SD).

as judged by panellists showing the highest correlation ( $r=0.966$ ) with increasing age.

### 3.5. Characterisation of the climacteric

Post-harvest respiratory profiles were determined for triplicate fruit of two different maturities (Fig. 6(A)–(B)). The respiratory climacteric in the mature fruit reached a maximum of 150–200 ml CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup> (Fig. 6(A)) while the younger, slightly immature fruit gave respiratory peaks of 300–350 ml CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup> (Fig. 6(B)). The climacteric occurred a few days later in immature fruit than in mature fruit but, regardless of maturity, there was only one climacteric maximum.

Irrespective of maturity, ethylene production coincided quite well with complete softening of the fruit (Fig. 6(A)–(B)). Surprisingly, however, for a fruit with such high respiratory rates, the levels of peak ethylene production were low at 0.7–1.2 and 1.0–1.5  $\mu$ l kg<sup>-1</sup> h<sup>-1</sup>, respectively, for mature and immature fruit.

## 4. Discussion

When the measurement of growth using linear parameters is compared with that assessed by fresh and dry weight, there is an obvious disparity between the growth kinetics (Fig. 1). Whether linear measurements were taken in situ or from fruit harvested for weight determinations, the single sigmoidal growth curve resulted. Thus, the possibility that the differences in growth curves could be attributed to differences in fruit samples was discounted. Furthermore, double sigmoidal growth was again evident for weight analyses performed the following year (November 1991–May 1992, data not shown). This disparity justifies

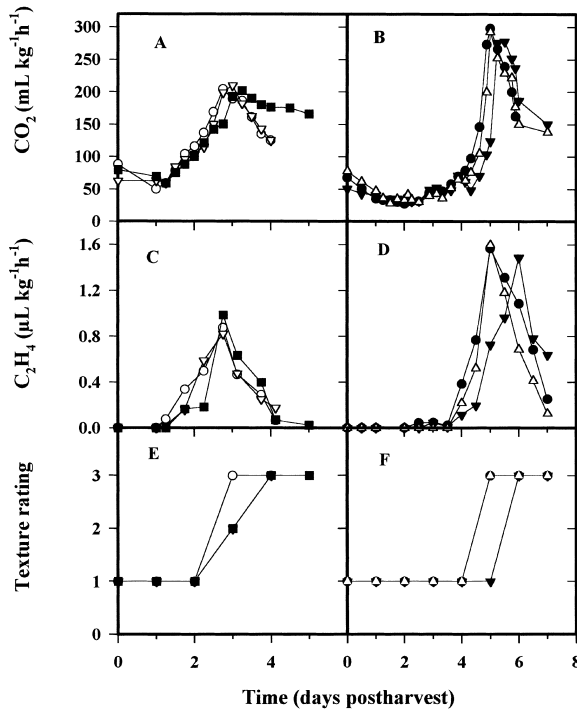


Fig. 6. Post-harvest changes in respiration (A, B), ethylene evolution (C, D), and texture (E, F) in 19- to 21-week-old mature (A, C, E) and 13- to 15-week-old early mature (B, D, F) breadfruit. Each symbol represents a single fruit.

warnings of Ryugo (1988) against using linear parameters alone to follow the growth of an organ and extrapolating from them.

Double sigmoidal, triphasic growth such as that seen in breadfruit weight analyses, comprising initial and final phases of rapid growth with an intervening period of reduced growth, is relatively common in fruit including blueberry, fig, grape, kiwifruit, pineapple, stone fruit (Coombe, 1976; Monselise, 1986) and soursop (Worrell et al., 1994). Pineapple and soursop, like breadfruit, are compound fruit, but others in this list are not. It is clear that double sigmoidal growth kinetics are not dependent on fruit-type, nor do taxonomic relatedness nor tropical/temperate origins dictate the pattern of fruit growth.

The intervening 'rest' phase in breadfruit growth is of interest. In some fruit, such a phase is associated with diversion of resources to embryo or endosperm growth or endocarp lignification (Monselise, 1986) but this is not the case in breadfruit which is seedless. Further, in other fruit with double sigmoidal growth, the intervening lag is not necessarily correlated with seed development, as is borne out by similar growth curves of seeded and seedless cultivars of both fig and grape (Bollard, 1970). Examination of rainfall patterns during the two breadfruit

growing seasons studied suggested that this lag might relate to a period of reduced rainfall. If, on the other hand, the lag is not environmentally imposed, then it may reflect the time required by the fruit to switch from size generation to laying down of reserves.

Full fruit size is reached around 15–16 weeks and though breadfruit can reach 2 kg or more, fruit in this study typically weighed 0.8–1.5 kg. With such variation, size is unreliable for estimating maturity. Fruit density was measured throughout development but this showed no reliable trend (data not shown). Similarly, the quantity of latex exuded on piercing either the fruit or peduncle in a standard manner showed no correlation with fruit age (data not shown). Skin colour changes, while evident, were too subtle to be a practical indicator of maturity. In contrast, fruit surface features such as polygon diameter and the relative flattening of polygons with the loss of a prominent central spike proved to be reliable, size-independent measures of maturity. We have successfully used these in conjunction with the occurrence of natural latex flow (in contrast to the induced latex flow referred to above) as maturity indices for this ‘white flesh’ breadfruit cultivar. Taste test results confirmed that these indices could be reliably used to identify fruit of optimum maturity for consumer acceptability and that such fruit were typically 15–19 weeks old. This indicates a 5-week period over which the fruit can be harvested and still be acceptable to the consumer and therefore has further implications for harvesting and marketing of the fruit.

The pattern of starch development also corroborated the designation of maturity indices. Starch accumulation increased from week 12 and reached a maximum between 16–20 weeks. This lends support to the view that the first 10 weeks of breadfruit development are primarily dedicated to size generation which, after a brief lag period, gives way to the final development phase characterised by weight gain, due largely to massive starch deposition. The actual starch content measured agrees with previous analyses for breadfruit (Graham and De Bravo, 1981; Wootton and Tumaalii, 1984). The pattern of high initial total and reducing sugar levels, declining with ensuing growth and development, and then rising as maturity approached, also agrees with data reported by Graham and De Bravo (1981). This may reflect the high sugar requirements for metabolism during the early developmental phase with low sugar levels in the latter phase reflecting the channelling of carbohydrate into starch.

Our finding of higher and delayed peaks of  $C_2H_4$  and  $CO_2$  production in less mature fruit compared to fully mature fruit (Fig. 6) has not been reported for breadfruit but a similar pattern is evident in avocado, mango (Tucker and Grierson, 1987) and soursop (Worrell et al., 1994). The large respiratory increase coincidental with ripening agrees with earlier work on breadfruit by Biale and Barcus (1970). These authors, however, reported a considerably lower value for the respiratory climacteric which may reflect their lower experimental temperature of 20°C and their comment that the respiratory maximum went beyond

the limits of their instrument. Breadfruit, like blackberry and avocado (Kader, 1985), is clearly a fruit with a very high respiratory rate. Such very dramatic increases in respiration rate, as well as peak CO<sub>2</sub> values, give some indication of the shelf-life of fruits (Biale and Barcus, 1970; Kader, 1985). Breadfruit is notorious in the produce trade for its perishability (Bell and Coursey, 1971) and this is compatible with its sharp respiratory rise and high respiratory peak.

The kinetics of C<sub>2</sub>H<sub>4</sub> evolution and respiration with coincident climacteric peaks contrasts with the pattern observed in other climacteric fruit such as tomato (Rhodes, 1979) and banana (Seymour, 1993) where the C<sub>2</sub>H<sub>4</sub> peak precedes the respiratory climacteric. The breadfruit pattern resembles fruit such as avocado and mango where C<sub>2</sub>H<sub>4</sub> does not rise before increase in respiration (Tucker and Grierson, 1987). The low peak C<sub>2</sub>H<sub>4</sub> production value of 1.0 µl kg<sup>-1</sup> h<sup>1</sup> measured in breadfruit is anomalous as most climacteric fruits, which have high respiratory rates, also have moderate-to-high C<sub>2</sub>H<sub>4</sub> production rates (Kader, 1985). Raspberry is one fruit which behaves similarly to breadfruit, as do vegetables such as cauliflower (Kader, 1985). Breadfruit's high perishability and low C<sub>2</sub>H<sub>4</sub> production rate reiterate the observation that there is no inviolate relationship between the C<sub>2</sub>H<sub>4</sub> production capacity of a given fruit and its perishability.

With this increased understanding of the development, maturation and ripening of this fruit, attempts must now focus on improving post-harvest handling procedures for this important tropical staple.

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