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Breadnut (*Artocarpus camansi* Blanco): A review of postharvest physiology, quality management, processing and utilization

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ABSTRACT

Purpose: This paper provides an in-depth critical review and analysis of recent research undertaken to optimize quality during harvesting, postharvest handling, processing and utilization of breadnut (*Artocarpus camansi* Blanco). **Findings:** This treatise provided a comprehensive review on the significance of breadnut as an ideal staple and famine food due to its abundance, processing options, high percentage of complex carbohydrates, unique flavor and culinary qualities. Market potential for this fruit across the globe and its projection to multiply is reviewed as related to increasing demand for fiber rich fruits, utilization in ethnic cuisine and in traditional medicine. The fruit is highly perishable with a shelf life of not more than 2-3 days under ambient conditions. Breadnut rapidly transforms when harvested mature green after 2-3 days to a soft texture and the outer skin of the milky white seeds change to a brown, brittle, tough netlike rind while the flesh changes from a white colour to a light yellow colour. The combined effects of rapid softening and high susceptibility to chilling injury contribute immensely to its short shelf life. **Limitations:** There were no significant limitations as the literature was available and access to communicate with authors were easily facilitated by the internet. **Directions for future research:** This is the only review which collated the findings on postharvest physiology and utilization of breadnut. This information will be useful for tree breeding programs, in order to popularize breadnut as a commercial crop and promote food security at the household and community levels.

INTRODUCTION

Breadnut (*Artocarpus camansi*) is native to New Guinea, and possibly the Moluccas (Indonesia) and the Philippines (Ragone, 2006). Widely scattered in alluvial forests in lowland areas in New Guinea, the fruit is naturally dispersed by birds and bats. In the Philippines and the Caribbean, breadnut is typically grown as a terrace tree as well as a land boundary marker. Breadnut is often considered to be a form of seeded breadfruit. However, it is a separate species and the ancestor of seeded and seedless breadfruit (*Artocarpus altilis*) (Roberts-Nkrumah, 2012).

The breadnut, in the West Indies, was brought by the French to the Caribbean ten years before the breadfruit was introduced by Captain Bligh (Coronel, 1994; Purseglove, 1974). Grown throughout tropical to subtropical areas, breadnut is an important source of nutrients, provide good timber, possess pharmacological properties, and widely used in folk medicine to treat a range of ailments. Three known members of the genus cultivated and utilized throughout the Caribbean and Asia and exported to ethnic markets in Europe and America include: breadnut (*Artocarpus camansi*), breadfruit (*Artocarpus altilis*) and jackfruit (*Artocarpus heterophyllus*). All trees of the Artocarpus genus produce sticky, white, milky latex that are present in all parts of the tree and contain a small quantity of rubber (Coronel, 1994).

Morphology and structure

The breadnut is characterized as a large monoecious tree with a spreading crown with a height of 10-15 meters or taller and a trunk one meter or larger in diameter often growing to a height of 5 meter before branching. Canopy diameter is distinguished as having about half of the tree height. It is a single-trunked tree with spreading evergreen canopy. Breadnut trees are typically integrated with buttresses at the base of the trunk (Ragone, 2006, 2011; Roberts-Nkrumah, 2012).

The leaves are designated as ovate to oblong ovate, coriaceous, 40-60 cm long, and 25-45 cm wide, bright, dark green, acuminate, deeply pinnate with 4-6 pairs of lobes that are ovate and acute with sinuses cut halfway to the midrib. The densely pubescent leaves are distinguished with many white or reddish–white hairs on upper and lower veins, lower leaf surface and petiole. The leaf blade is dull green with green veins. Two large green stipules enclose the bud, turning yellow before dehiscing (Barrau, 1976; Brown, 1943; French, 1988; Roberts-Nkrumah, 2015).

Importance and economic value

The global demand for breadnut fruit has accelerated dramatically over the past 18 months (FMI, 2020). Furthermore, North America is holding the largest market share for breadnut fruit market due to adaptation in gymnastic and beauty products (FMI, 2020). Global Industry Analysis (2012 – 2016) and Opportunity Assessment (2017 – 2027), projected that due to increasing demand for fiber rich fruits, Asia Pacific will hold maximum market share for breadnut in the near future. Breadnut contains omega-3 fatty acids that can easily control and sustain healthy and balanced levels of cholesterol, reinforce bones build-up and encourage mental health by reduction of the likelihood of bipolar problems (FMI, 2020).

Culinary uses

Breadnut is versatile with diverse culinary uses at different stages of maturity. In the Caribbean, mature green fruits including the pulp and immature seeds are cooked with curry, coconut milk and even meat forming an exotic meal with roti or rice. At the cottage level, the sweet granular layer on the fruit core as well as the seedless pulp are used to make milk based beverages (Mohammed &Wickham, 2011).

Table 1. Physicochemical and sensory quality attributes of breadnut at horticultural and physiological stages of maturity †

Quality profile	Horticultural maturity (Weeks after fruit set)		Physiological maturity (Weeks after fruit set)	
	8 weeks	10 weeks	11 weeks	12 weeks
Fruit wt. (g)	719	1101	1200	1240
Spine 5/3 cm^2	30	23	21	20
External skin colour				
"L"	38.3	36.8	36.8	36.28
"a/b"	-0.4	-0.5	-0.47	-0.26
Flesh colour				
"L"	82.7	85.2	82.9	72.34
"a/b"	-0.3	-0.3	-0.29	-0.31
External seed colour				
"L"	85.7	82.7	75.4	43.9
"a/b"	-0.03	0.02	0.18	0.44
Internal seed colour				
"L"	85.6	87.4	86.4	82.1
"a/b"	-0.16	-0.14	-0.14	-0.12
Fruit firmness (g/force)	743.1	880.5	890.5	17.5
Seed firmness (g/force)	225.6	429.3	646.3	787.5
Seed length (cm)	2.6	2.8	2.8	3.1
Seed width (cm)	2.3	2.2	2.4	2.5
Seed dry matter (%)	13.3	26.9	32.5	39.2
Seed germination (%)	16.8	98.0	99.5	99.8
Seed reducing sugar (%)	15.6	2.6	2.0	3.4
Seed total sugars (%)	19.1	4.3	4.5	5.9
Flesh dry matter (%)	12.7	13.9	14.1	16.4
Flesh reducing sugar (%)	2.6	3.0	12.6	12.9
Flesh total sugars (%)	3.5	4.2	13.9	14.1
Seed eating quality *	1.9	4.5	4.8	4.89
Flesh eating quality *	4.0	4.8	1.0	1.0

† (Mohammed and Wickham, 2011)
*Cooking and eating quality rating 1-5 with 1= disliked and unacceptable, 2= disliked, 3= liked slightly, 4= liked moderately and 5= liked extremely.

Table 2. Organoleptic quality of cooked breadnut seeds evaluated from fruits harvested 12 weeks after fruit set followed by an additional 10 and 17 days respectively in ground storage †

Duration after fruit set	Quality rating[z]	Eating quality properties
12 weeks	4.9c	smooth texture, slightly sweet taste, glossy brown seed testa with light brown inner coat lining, cream coloured germinating embryo.
12 weeks + 10 days ground storage[y]	3.0b	smooth texture, very slight sweet taste, dark brown seed testa with light brown inner coat lining, brown coloured germinating embryo.
12 weeks + 17 days ground storage	1.9a	hard texture, bitter taste, black seed testa with dark brown coat lining, light green germinating embryo.

† (Mohammed and Wickham, 2011)
[z] Cooking and eating quality rating 1-5 with 1= disliked and unacceptable, 2= disliked, 3= liked slightly, 4= liked moderately and 5= liked extremely. $LSD_{0.05}$=0.9.
[y] Ground storage: period fruit remains on the ground with seeds embedded in pulp.

Fruits harvested at the physiological stage of maturity contain pre-germinated seeds characterized with a light brown brittle-like seed coat. Underneath this seed coat is a light brown thin papery-like lining surrounding the seed mesocarp. Mature seeds when separated from the soft pale yellow pulp and boiled for 30-40 minutes in water with the inclusion of salt make a very tasty nutritious snack in the Caribbean and African countries (Amadi, et al., 2019; Bridgemohan & Mohammed, 2019). Similar in taste and texture to chestnuts, breadnut seeds could be commercialized when roasted, canned in brine, or processed into breadnut butter or breadnut paste or oil (Bridgemohan & Mohammed, 2019; Harnarine, 2019). Boiled breadnut seeds could also be made into value-added products such ground paste that can be fried or baked and used in the formulation of palatable high-protein infant foods suitable in traditional culinary and child feeding practices throughout the world (Nelson-Quartey et al., 2007). The boiled or fried seeds can also be used as a substitute for chickpeas (*Cicer arietinum*) (Harnarine, 2019). Studies have advanced the culinary properties of breadnut as a high quality protein source for food products (Amadi et al., 2019). As a meat replacement for ground beef meat balls in the Philippines, Zamora et al. (2017) evaluated the sensory quality attributes of different ratios of breadnut fruit and ground beef. They concluded that 25% breadnut combined with 75% ground beef was the most accepted formulation with a shelf life of two weeks with no added preservatives.

Mohammed and Wickham (2016) investigated the sensory quality attributes of breadnut fruits harvested at horticultural and physiological stages of maturity. They reported that the cooking and eating quality of breadnut fruits harvested before week 8 had an unacceptable rating. The immature seeds were soft and gel-like in texture forming a gluey mass upon cooking with the tender flesh and this resulted in a distinct off-taste as recorded by the panelists with ratings averaging 2.5 and under. Fruits harvested between weeks 8-10 had cooking and eating quality rated as highly acceptable but the highest rating of 4.8 was given for fruits harvested 10 weeks after fruit set. Physico-chemical attributes varied for flesh and seeds of pre-cooked fruits that were harvested at horticultural maturity. Earlier, Mohammed and Wickham (2011) summarized their findings on the organoleptic quality of cooked breadnut seeds based on evaluations from a 65-member trained panelists in Trinidad and Tobago (Tables 1 and 2, Fig. 2a).

At the Cebu Technological University in the Philippines, Go et al. (2015), investigated the acceptability, shelf life and the nutritional quality of formulated breadnut chocolate cookies (BCC) from breadnut seed flour (BSF). The cookies were prepared using different ratios of all purpose flour (APF) and breadnut seed flour in percent (0:100, 25:75, 50:50, 75:25, 100:0) with 100 percent all purpose flour served as the control. Based on results from 50 respondents, they concluded that all formulated breadnut cookies were acceptable. The cookies with 50 percent BSF were the most acceptable product. The formulated cookies had significant amounts of nutrients and regarded as safe with guaranteed desirable sensory properties with a shelf life six (6) months.

At the Food Science and Technology Department, Federal University of Technology, Nigeria, Malomo et al. (2011), assessed the quality of bread produced from breadfruit and breadnut-wheat composite flour. In their investigation, six blends were prepared by homogenously mixing breadfruit and breadnut flours with wheat flour in the percentage proportions: 5:95, 10:90, 15:85 (BF: WF and BFN: WF) to bake bread and examined their chemical, rheological and physical properties. They inferred that breadfruit and breadnut could be added to bread up to levels of 15% (flour basis) without significant adverse effects on quality attributes such as crust color, crumb structure and uniformity. Apart from sensory properties, breadfruit flour and breadnut flour supplemented bread samples were more acceptable in many nutritional aspects as they contained significantly more protein, copper, zinc, and fat.

Noah and Ogonfowote (2017), indicated that fermented breadnut seed can be used as condiment in soup because it consisted of beneficial microorganisms which increased the nutritional value of food and reduced microbes associated with food-borne diseases that can be hazardous to health. Amadi et al. (2019), further advocated that boiling and fermentation enhanced the essential amino-acids as well as minerals such as calcium, magnesium, iron and zinc contents of breadnut seed flour while reducing the fat, vitamins A and C contents. Furthermore, it was advocated that consumption of processed breadnut seeds via boiling and fermentation could be extended as food fortificants in the production of infant complementary foods and confectionaries.

Nutritional values

The breadnut has a moisture content of 56%, which is lower than that of the breadfruit and consequently, hence it is more energy and protein dense. The edible pulp constitutes 33.2-46.8% of the fruit while the seed constitute 30.1- 46.8% (de Bravo et al., 1983; Mohammed and Wickham, 1996). Breadnut seeds contain high quantities of calcium, phosphorus, potassium, iron and niacin compared to other tree nuts. The fiber content of the seeds ranged from 2.5-3.9g, whereas in the edible pulp the fiber content could be as high as 18.0g (de Bravo et al., 1983). Adaku et al. (2019) evaluated the dietary fiber and fatty acid composition of boiled, roasted, fermented and germinated breadnut seed flour. They recommended breadnut seed flour as a wheat substitute for the bakery industry, as well for culinary uses and weight loss initiatives. Their studies indicated that the dietary fiber contents of the processed breadnut seed flours were higher compared to reports by Oladele and Oshodi (2013) but lower than that investigated by Echendu et al. (2009). The dietary fiber content in the roasted breadnut flour had the highest value while fermented breadnut flour had the lowest amount of dietary fiber. The high dietary fiber content of the roasted breadnut seed flour was consistent with the results of Azizah et al. (2009). They related the increased dietary fiber content to the effect of Maillard reaction.

A 100g portion of dried seed consists of 13.3-20g protein. Four amino acids, methionine (3.2g), leucine (2.6g), isoleucine (2.4g) and serine (2.1g) account for more than 50% of the amino acids (de Bravo et al., 1983).

Adeleke and Abiodun (2010) analyzed matured breadnut seeds for proximate composition of minerals, amino acids, fatty acids and organic acids. Their results identified the proximate composition of the breadnut seeds as: protein (4.87%), fat (3.48%), carbohydrate (26.11%), ash (3.43%) and crude fiber (1.20%). The highest mineral content value was in phosphorus 363 mg/kg followed by potassium 325 mg/kg and sodium 248 mg/kg while the lowest value was in iron 0.05 mg/kg and copper 0.12 mg/kg. The predominant essential amino acids in the seeds were leucine 392 mg/kg, phenylalamine 312 mg/kg, arginine 293 mg/kg, isoleucine 245 mg/kg and lysine 275 mg/kg. The oil was rich in palmitic 21.4%, oleic 12.4% and linolenic acid 14.8%. Their analysis also showed that breadnut seeds were low in organic acid content with the predominant acids being lactic acid (0.317 mg/kg) and citric acid (0.185 mg/kg). The seeds exhibited trace amounts of acetic acid (0.050 mg/kg), butyric acid (0.012 mg/kg) and malic acid (0.012 mg/kg. From this study in Nigeria it was articulated that breadnut seeds could be formulated to make composite flour while the extracted oil could be used as an edible oil (Adeleke & Abiodun, 2010).

Rabeta and Nor Syafiqah (2016) from the Malaysian Agricultural Research and Development Institute, investigated the proximate composition, mineral and total phenolic contents (TPCs), and antioxidant capacity of the core, pulp and seed of breadnut (*Artocarpus* *camansi*). For proximate composition, pulp had the highest ash (1.47%) and protein contents (1.29%), and core had the highest moisture content (88.6%). The minerals present in breadnut were calcium, zinc, copper, manganese, iron and sodium. The values were different and lower than the previous studies cited above possibly because of the difference in growth habits, soil type, water source and cultural practices adopted during planting (Adeleke & Abiodun, 2010). The highest percentage inhibition of 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity was observed in the methanolic extract of breadnut seed, followed by pulp and core. The lowest scavenging activity was found in the breadnut pulp using water extraction. To encourage industrial adoption, further research on toxicity tests and the incorporation of breadnut fruit in processed food products, such as beverages, yoghurts, and flour for pastries, and evaluation of the microbial and sensorial qualities of such products are necessary.

Oshodi et al. (1999) investigated the chemical composition, amino acid analysis and functional properties of breadnut flour and reported that this value-added product contained 55.1% high quality proteins and amino acids, which is higher than the protein and amino acid levels of soy flour and egg. They elucidated that the dominant essential amino acids were valine, glutamic acid, aspartic acid while the limiting amino acids being methionine and cysteine. They also claimed that the breadnut protein had minimum solubility at pH 5 and maximum solubility at pH 8. Potassium was the most abundant mineral in the breadnut flour (0.7g /100g^{-1}), while magnesium (0.08g /100g^{-1}) as the least. Additionally, breadnut flour was identified as a useful thickener and a source of dietary protein. Nwabueze (1999), further investigated the effect of blanching on the composition of breadnut flour and found that while the raw and blanched flours showed low protein (4.6%) and fat (14.25%) but high carbohydrates (66.33%), blanching only improved the carbohydrate content, which increased to 70.45%. Blanching upgraded the physical characteristics of the breadnut flour by promoting the “meat” extraction rate from 80.5% to 86.0%, wettability from 1.38 to 0.56 min and bulk density from 0.66 to 0.82 w/v due to the effect of heat on the components native to the breadnut.

Fagbemi et al. (2005) reported on the effects of processing such as raw drying, boiling, fermenting, germinating and roasting on antinutritional factors and in vitro multienzyme protein digestibility of three tropical seeds including breadnut seeds. Their results indicated that processing significantly affected the antinutritional factors in the flours. Breadnut flours contained 2.8- 5.3g kg^{-1}, phytic acid 5.9-9.2g kg^{-1} tannin and 0.9-8.1mg g^{-1} of trypsin inhibitor activity. Fermentation proved to be the most effective processing method to reduce phytic acid and trypsin inhibitor activity while boiling was most effective in reducing the tannin content. Their results also confirmed that in vitro multienzyme protein digestibility of seeds generally showed that the boiled samples were the most digestible followed by the fermented samples while the raw /germinated samples were the least.

Health benefits

Medicinal properties of various parts of the breadnut tree other than the flesh and seeds have been investigated and reported to have traditional local remedies for ailments in various parts of the world. The flowers are roasted in Java and rubbed on infected gums to reduce toothache. The yellow senescing leaves are boiled and used in several rural communities in the Caribbean to alleviate diabetes and hypertension (Bridgemohan & Mohammed, 2019). The reduction in blood pressure could be attributed to the presence of amino-butyric acid in the yellow leaves (Brown, 1943., Ramos-Ruiz et al., 2019). In the West Indies, the sap is used by chiropractors and massage therapists as a plaster to assist in healing dislocated joints. Breadnut is rich in histidine, an amino acid that is popularly used as an alternative medicine for the treatment of rheumatoid arthritis among other diseases. Amino acids have pain-relieving properties. Complementary and alternative medical practitioners in rural districts in Trinidad have commented on the high antioxidants on the breadnut tree bark that can be used to boost the body's action against infectious viruses (Harnarine, 2019). Breadnut could also be used to enhance dental hygiene, prevent bone loss, aid in digestion, heal skin conditions, improve blood clotting, prevent anemia and improve cardiac health (Ricker & Hass, 2017., Harnarine, 2019).

Ante et al. (2016), studied the volatile composition of the leaf, stem-bark, and nut of *Artocarpus camansi* at the University of Karachi, Pakistan. Essential oils were obtained by hydrodistillation. A total of 32, 11, and 26 compounds were identified, representing 99.09%, 99.45%, and 99.89% acquired from the leaf, stem-bark, and nut oils, respectively. The main constituents of the leaf oil were *m*-xylene (36.82%), myristaldehyde (25.36%), phytol (6.21%) and ethyl benzene (7.25%). Essential oil derivatives from the stem-bark were *m*-xylene (61.32%), *o*-xylene (18.76%), and ethyl benzene (16.21%). Components of the nut oil were lanosteryl acetate (23.9%), olean-12-en-3y acetate (23.63%), 24-methylene cycloartenol (17.57%), *m*-xylene (15.26%), and squalene (2.85%). These essential oils accounted for varying levels of antimicrobial resistance effectiveness, ranging from low to moderate, depending on the oil composition, plant part and specific microoganism. Further studies are warranted to determine the efficacy and resilience against resistant microbial strains using different combinations of the essential oils procured from breadnut plant parts. Likewise, clinical trials to verify the folklore medicinal remedies of the breadnut plant described above should be conducted.

Factors affecting quality

Pre-harvest

Breadnut trees can adapt to a wide range of ecological conditions. Trees grow best in equatorial lowlands below 600-650m but are found at elevations up to 1550m. Breadnut trees can tolerate short dry periods (Ochse et al., 1961). An annual rainfall of 150 cm and a temperature of 21-30^{0}C is ideal for growth and development. Trees are tolerant to a wide range of soil types but perform best in deep, fertile, well drained, sandy loam or clay loam soil. Seeds should be planted 5cm apart and 1cm deep. Seeds begin germinating in 10-15 days after sowing. When seedlings are 1-year-old it is ready for field planting. Plants are spaced 12-15 meters apart. Trees begin production after 8-10 years. Small branches often die back at the tip after fruiting, but new shoots and branches continue to develop throughout the life of the tree (Ragone, 2011; Roberts-Nkrumah, 2012).

Flowering is monoecious with male and female flowers on the same tree at the ends of branches; with the male inflorescence appearing first. Male inflorescence is club-shaped, rather spongy, curved at the base, cylindrical, greenish-yellow, 15-20 cm long and 3-4cm in diameter (Fig. 1a). Thousands of tiny flowers with two anthers are attached to a central spongy core. Female inflorescences are ovoid with pubescent petiole and two-lobed elongated and prominent stigma and consist of 1500-2000 reduced flowers attached to a spongy core (Coronel, 1991).

Fruits of the breadnut tree consist of a large fleshy syncarp, oval or ovoid, 13-20 cm long and 7-12 cm in diameter, weighing approximately 800-1200 g (Fig. 1a and 1c). When ripe, the skin has a dull green appearance with randomly scattered areas of soft spine tips with a pale brown colour. The pulp is whitish-yellow when ripe with a slightly sweet aroma and taste. The fruit is not as solid or dense as other fruits in the family because the individual flowers forming the fruit are fused together only at their bases. The fruits contain numerous seeds, from 12 to as many as 150, each weighing an average of 7-10 g, comprising 30-50% or more of the total fruit weight (Roberts-Nkrumah, 2005).

Roberts-Nkrumah (2005) reported that the highest fruit mass per tree to be 139.7 kg, fruit number per tree as 126 and seed mass per tree as 59 kg in 5-year old trees. Additionally, fruit seed yields were significantly lower in the years after pruning. Fruit mass per tree was positively correlated with fruit number (r = 0.99). Her study also indicated that seed mass per fruit was positively correlated with seed number per fruit (r = 0.87) and both variables had strong, positive correlations with mean fruit mass (r = 0.83 and r = 0.77, respectively) and fruit volume (r = 0.63 and r = 0.77, respectively). Roberts-Nkrumah (2005) emphasized that breadnut fruit and seed yield as being greater than originally estimated and emphasized further that both are strongly related and therefore selection for high seed number per fruit with more effective pollination, disease control and proper tree height management may increase productivity. This study which was conducted at the University of the West Indies Field Station in Trinidad, also confirmed that estimated fruit volume is the most practical indicator of seed yield.

The fruit is generally available year round but usually the season extends from June to November in most Caribbean islands. In Trinidad and Tobago, the peak season is from October to November. Roberts-Nkrumah (2005, 2012) studies showed that over a 7-year period, the mean total fruit mass per tree and per year was 52.7 kg and the mean fruit number per tree was 49. Mature breadnut trees in the Philippines have been reported to produce 600-700 fruits per season. Based on 100 trees/ha producing 200 fruits per tree, an average yield of 11 mt/ha of fresh seeds has been estimated (Ragone, 2006).

Fruit growth and development

Growth and development of the breadnut fruit depicted a typical sigmoid shape. Mohammed and Wickham (2011), identified changes in the breadnut fruit growth from 6 weeks after flowering with an average weight of 455.3g until 12 weeks where the average weight increased to 1240g (Fig. 2b). Fruits examined 6 weeks after fruit set had seeds that were undeveloped, soft internally, with a jelly-like appearance and having an eating quality rated as poor. Although fruit weight increased by another 100g by the end of the seventh week postanthesis, fruits were still considered as immature based on the poor eating quality. Fruit weight increased rapidly from week 8 to week 12 (Fig. 2b). Fruits harvested between weeks 8 to 10 which ranged between 719 g-1101 g were horticulturally mature (Fig. 1b) with excellent cooking and eating quality (Tables 1 and 2).

At weeks 11-12 fruit fresh weight measured between 1200-1240 g, reaching a plateau indicative of attaining physiological maturity (Fig. 2b). Coinciding with increasing fruit weight was a similar increase in firmness up to week eleven postanthesis. Noteworthy, was the relatively small increase in firmness from weeks 9 to 11 (Fig. 2c). Moreover, from week 11 to 12 the breadnut fruit exhibited a dramatic decline in firmness accompanied by fruit ripening (Fig. 2c). During fruit development increasing fruit weight was accompanied by a decrease in the number of spines per $3cm^2$ on the fruit skin from weeks 6-12 after fruit set. Fruit mass after 6 weeks following fruit set was 2-folds greater three weeks later and nearly 3-folds more by week 12. Meanwhile, the number of spines at week 6 which amounted to 45 per $3cm^2$ decreased to 20 per $3cm^2$ at week 12 thereby confirming an inverse relationship between fruit weight and number of spines on the fruit surface (Mohammed and Wickham, 2011).

Fig. 1a. Breadnut flower and immature fruits

Fig. 1b. Mature breadnut

Fig. 1c. Internal section of mature fruit

Fig. 1d. Ripe fruit with brown skin, soft flesh and mature seeds

Fig. 1e. Enzymatic browning of flesh

Fig. 1f. Physical damage

Fig. 1g. MAP of mature fruit

Fig. 1h. Seed testa color changes

Fig. 1i. Chilling injury (CI)

Fig. 1j. CI seed translucency

Fig. 1k. CI seed discoloration

Fig. 1. Growth, development, maturation, ripening, physical damages and chilling injury of breadnut (a-k). (Mohammed and Wickham, 2011).

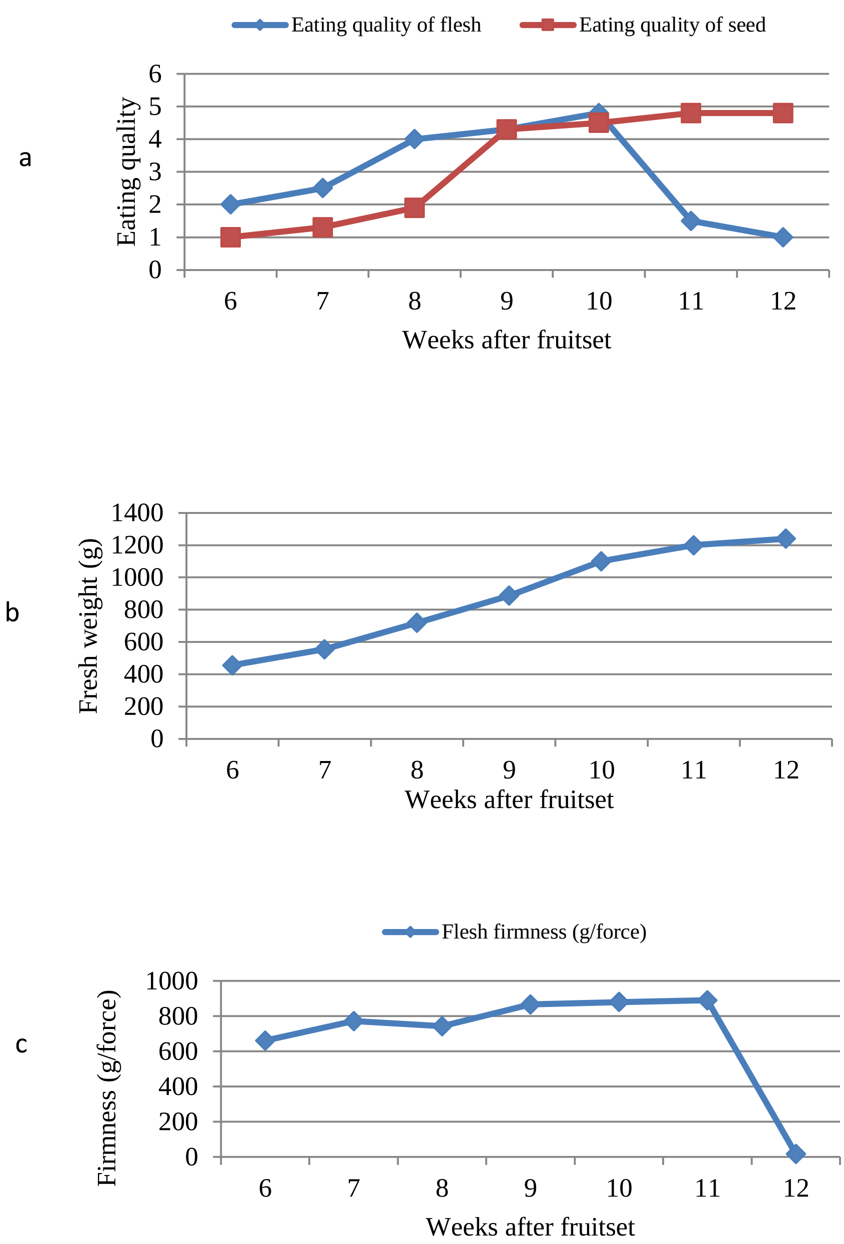

Fig. 2. Changes in eating quality (a), fresh weight (g) (b) and flesh firmness of breadnut (c) (Mohammed and Wickham, 2011).

Indicators of fruit maturity

Progress at horticultural maturity was not associated with any significant changes in skin or flesh colour and therefore skin and flesh colour are unreliable indicators of maturity (Table 1). However, the seed testa did undergo major changes in colour from white to brown as fruit advanced in maturity (Fig. 1d and 1h). Moreover, the seed testa and endosperm got firmer with time. There was an increase in percentage seed germination as well as percentage seed dry matter content. Thus the colour of the seed testa, seed germination and dry matter percentages were reliable indicators of fruit maturity (Table 1).

Changes during fruit maturation and ripening

Respiration and ethylene production rates in breadnut have not been determined and currently research is being conducted to investigate the respiratory pattern of this fruit. Major physical and chemical changes accompany fruit ripening at the onset of physiological maturity, that is, between weeks 11 and 12 after fruit set. These ripening changes are summarized in (Tables 2 and 3).

At horticultural maturity, that is, weeks 8-10 after fruit set, fruit mass ranged from 719 g to 1101 g which corresponded with decreased spine spacing from 30 per 3cm^2 to 23 per 3cm^2 over the same period (Mohammed and Wickham, 2011) (Table 1). The seeds normally eaten together with the flesh when cooked at this stage of maturity, ranged in size from 2.6-2.8 cm in length and 2.3-2.5 cm in width with a mass of 64.7-70.9 g, had a milky-white seed coat with a 'L' value of 82.7-85.7 and 'a/b' ratio of -0.02 to -0.03 (Table 1). Fruits at this stage of maturity also had lower sugar levels for the flesh and seeds compared to earlier or later periods (Table 1). Percentages dry matter of flesh and seed varied between 12.7-13.9% and 13.3-26.9% respectively while percentage seed germination ranged from 16.8-98.0% according to investigations conducted by Mohammed and Wickham (2011) (Table 1).

In a series of experiments conducted by Mohammed and Wickham (2003, 2004, 2011, 2016), they described breadnut fruit ripening as being initiated towards the end of 10 weeks after fruit set which progressed rapidly in week 11 accompanied by dramatic physicochemical changes at week 12. Ripe breadnut fruits harvested in week 11 would not produce copious amounts of latex at the detached peduncle nor from the broken spines as before. Fruits harvested at week 11 had a dull green appearance with randomly scattered areas of soft spine tips with a pale brown colour (Fig. 1d). At this stage of maturity, the peduncle is dominated with a yellowish-brown colour, the abscission zone is significantly weakened thereby allowing easy fruit detachment. Detached ripe fruits are brown in colour throughout the entire surface as "a/b" values decreased significantly from -0.47 at week 11 to -0.26 at week 12 (Table 1). The light cream flesh with "L" being 82.9 and "a/b" being -0.29 at week 11 changed to bright yellow at week 12 with "L" being 72.34 and "a/b" being -0.31 (Table 1). Noteworthy was the sticky nature of the soft flesh which embedded the seeds at various locations within the fruit (Fig. 1d). The fruit core was brown in colour with a soft sandy texture.

Table 3. Changes in color of skin, flesh, external seed and internal seed of breadnut from weeks 6-12 after fruit set †

Weeks after fruit set	Skin color		Flesh color		External seed color		Internal seed color	
	L	a/b	L	a/b	L	a/b	L	a/b
6	35.8a	0.45bc	83.4cd	-0.31a	82.6d	-0.06a	74.3	-0.07
7	35.6a	0.46bc	81.7bc	-0.31a	87.8d	-0.06a	85.3c	-0.17d
8	38.3b	-0.44b	82.9bcd	-0.29a	85.6c	-0.03	85.6c	-0.16c
9	36.1a	-0.44b	80.9bc	-0.29a	82.3c	-0.08b	84.7c	-0.16c
10	36.8a	0.49cd	85.2d	-0.31a	82.7c	-0.02a	87.4d	-0.14bc
11	36.8a	-0.47	82.9bcd	-0.29a	75.4b	0.18c	86.4c	-0.14bc
12	36.3 a	-0.26a	72.4a	-0.31a	43.9a	0.44d	82.16	-0.12b
LSD (0.05)	1.8	-0.02	2.4	-0.02	3.05	0.03	1.56	0.02

† (Mohammed and Wickham, 2011)

a

b

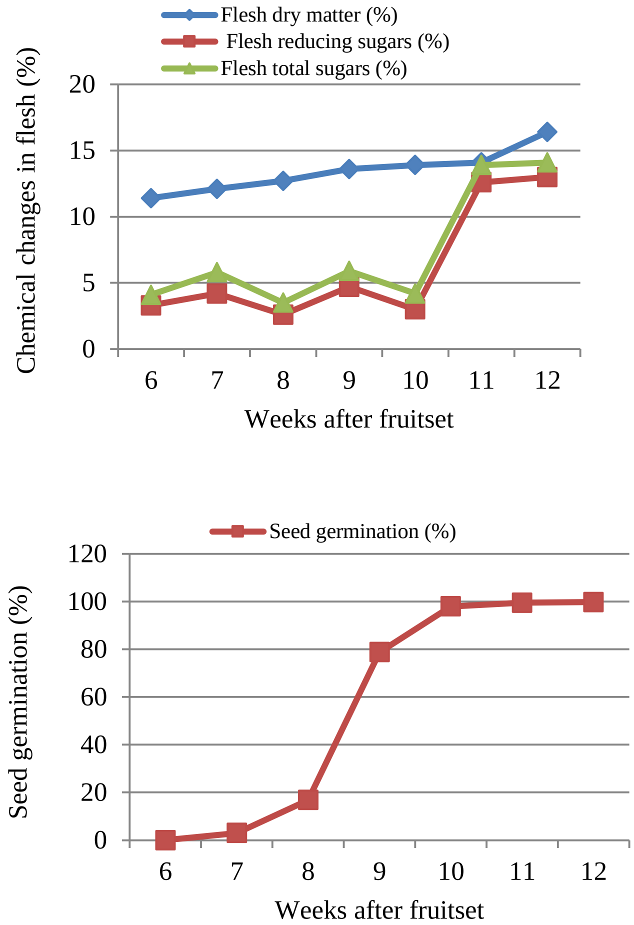

Fig. 3. Changes of breadnut flesh dry matter, reducing sugars and total sugars (a), and seed germination percentage (b) (Mohammed and Wickham, 2011).

The most dramatic change in breadnut fruit ripening was the rapid decline in flesh firmness between week 11 and week 12. Here a decrease in firmness was almost fifty-one times more at week 12 compared to week 11 (Fig. 2c). Breadnut seeds had incremental increases in firmness as fruit ripening progressed from 10 weeks onwards.

Breadnut flesh and seed showed major changes in percentage dry matter during ripening between weeks 10-12 after fruit set. Accordingly, percentages dry matter were at least two folds higher for seeds compared flesh at week 10. However, while percentage dry matter for flesh was only significantly higher between week 10 and week 12, in the case with the seeds this occurred between each consecutive week (Fig. 3a; Table 1).

The onset of ripening coincided with other major chemical changes between weeks 10-11 which progressed even faster between weeks 11 and 12 after fruit set. Between weeks 10 and 11 significant increases were obtained for flesh reducing and total sugars (Fig. 3a). Reducing sugars in breadnut flesh increased from 3% at week 10 to 12.9% two week later, accounting for more than a four-fold difference (Table 1). Likewise, total sugars of the flesh over the same time intervals increased from 4.2% to 14.1% resulting in a significant reduction on the hedonic scale used by panelists for determining eating quality of the cooked flesh and seeds from a highly acceptable rating of 4.8 for fruits selected at week 10 compared to a rating of 1.0 at weeks 11 and 12 respectively (Table 1).

Postharvest quality management

Harvesting operations

Plant height and fruit size and weight at different stages of maturity could create major challenges during harvesting operations. Weakening of the natural fracture line at the point of fruit attachment at the abscission layer on tree branches could be induced during fruit ripening and softening to accelerate natural fruit drop on hard ground surfaces resulting in a shattering of fruit pulp (Mohammed and Wickham 2011; Bridgemohan and Mohammed, 2019). A similar occurrence could result more so when harvesting devices without collecting pouches are used. However, the wholesome nature of seeds is protected from physical damages due to the buffering effect which cushions each seed that is embedded within the disintegrated fruit pulp (Bennett and Nozzollilo, 1988). More often, only the fruit seeds are utilized into a range of value-added products as published and described extensively above (Amadi et. al 2019; Adaku et. al 2019). If left unattended, for over 3 days, fruit pulp and seeds embedded in pulp become susceptible to secondary infections, which is dominated on the soft pulp. Frequently, the senescing ripe fruit pulp with embedded seeds are usually allowed to remain on the ground for 1-3 days. Pectolytic enzymes from the senescing pulp would enhance further degradation of the pulp thereby making seed removal easier and less cumbersome (Bridgemohan and Mohammed, 2019).

Harvesting of breadnut fruits at the horticultural stage of maturity (that is, week's 8-10 post-anthesis) should ideally be carried out on the day of marketing and display for sale or on the previous day, if cool storage and adequate supervision of grading and packing are available. Preferably, harvesting operations should be conducted in the early part of the morning or late in the evening to minimize buildup of field heat. Breadnut fruits should be harvested individually to minimize physical damages. Fruits at different stages of maturity could be located in a cluster, so care must be taken at harvest to select only fruits that are at the appropriate stage of maturity to minimize breakages of spines due to abrasions. Picking poles with attached pouches should be used. Fruits must be harvested with the peduncle attached at the stem end and the attached peduncle should be at least 9-10 cm in length (Roberts-Nkrumah, 2015; Mohammed and Wickham, 2011).

Breadnut fruits located on lower branches should be snapped from the tree at the point adjacent to the branch. When the peduncle is cut, the fruit should not be allowed to drop and should be caught by hand or in a net, before sustaining the impact associated with ground collision in order to reduce major physical damages such as spine breakages, cracks, punctures and abrasions (Fig. 1f). Physical damages could facilitate the proliferation of soil borne pathogens, moisture loss and secondary infections. Even collection of fruits with a picking pole with an attached pouch can cause adjacent fruits to rub against one another causing the spines to break at the tips which could trigger the exudation of milky latex to induce staining of the external skin (Fig. 1f). Additionally, breadnut fruits should never be allowed to be knocked from the tree, dropped or thrown directly on the ground, as the resultant bruising and breakages of spines and skin fissures would induce secondary infections eventually leading to rapid senescence.

The elongated peduncle from the harvested fruit should be removed with a sharp stainless steel knife in order to ensure that the peduncle is flush with the level of the fruit shoulders or slightly protruding to a maximum length of 1.5-2.0 cm. Peduncle trimming should be conducted in the field immediately following harvest. The fruits should then be placed downwards on a clean surface, perhaps on broad leaves such a banana leaves or a sanitized tarpaulin to permit latex drainage. Out grading of immature, undersized, damaged, bruised, scarred, punctured or ripe fruits can be undertaken in the field under shade or in the packinghouse. Following latex drainage harvested fruits should be placed in a single layer in shallow, light coloured, well ventilated field crates. Harvested breadnut fruits must never be exposed to the sun, be it under field conditions or during transportation to the packinghouse. Marketable fruits should be immersed in a tank containing 100 ppm sodium hypochlorite for sanitizing purposes and also to rinse any residual field materials, latex and other debris. Prior to packing fruits should be placed in plastic crates and allowed to air dry (Mohammed and Wickham, 2011; Roberts-Nkrumah, 2015; Harnarine, 2019).

Pre-cooling and temperature management

Breadnut fruits would benefit from rapid removal of field heat following harvest and can be hydrocooled providing that the temperature of the water is not below 10-12ºC. Iced water or air systems below this temperature should be avoided as this could result in browning on the fruit surface as well as on the spines. Room cooling is recommended but would be slow particularly if stacking and ventilation are inadequate or if the cooling capacity of the system is low.

Transpiration

The breadnut flesh is porous and despite the presence of spines if fruits are kept in storage where the relative humidity is below 85-90% water loss would be promoted. Mohammed and Wickham (1996) reported that the modified atmosphere packaging (MAP) technique applied to fruits individually sealed in low density polyethylene bags (LDPE) accounted for reduced water stress compared to fruits stored as controls in paper bags (Fig. 1g). Accordingly, after 2 days at 28-30ºC, fruits kept in LDPE bags had a reduction in percentage fresh weight loss of 2.02% compared to their counterparts stored in paper bags which measured 7.05%. Control fruits had a seven-fold increase in fresh weight losses after 4 days at ambient temperature compared to individually sealed fruits in LDPE bags. Regardless of the type of packages used, fruits succumbed to multiple pathological infections and appeared dried and withered and were rendered unmarketable after 4 days at 28-30ºC.

Packinghouse operations

Packinghouse operations are critical to ensure fruits at the optimum stage of maturity are selected. Due to latex exudation and subsequent brown discolourations at the cut stem end and from spine breakages, a water dip is essential. Quality checks are required prior to packing to ensure the removal of all fruits not meeting market requirements, particularly in terms of maturity and mechanical damage. Fruits should be graded according to size, external skin colour, denseness, absence of defects arising from physical damages, distorted fruit shapes and decay. Fruits should be individually sealed in LDPE bags and placed one layer of 5-7 fruits in double layered cardboard cartons.

Fruits should be graded in each carton according to the size. Net weights per cartoon should range from 12-16 kg. Each individual carton should be weighed, and the carton marked and labeled according to market destination. Cartons should not be overfilled during packing. The following systems of fruit sizing is recommended: large (2.0-2.5 kg), small (1.1-2.0 kg). The bulk packaging should be full telescopic two-piece fiberboard cartons or one-piece self-locking waxed cartons. Fruit dividers would be desirable as this would reduce fruit movement and rubbing. Recommended carton internal dimensions are 20 by 51 by 34 cm or 29.5 by 44 by 29.5 cm. For air transport it is recommended to store fruits at 8-9ºC and 90-95% RH. Short delays and high temperatures, low relative humidity within aircraft containers with no ventilation would encourage heat build-up and ethylene resulting in abbreviated shelf-life (Mohammed and Wickham, 2011).

Storage under ambient conditions

Storage of seeds in excess of 4-5 days under ambient conditions resulted in the brittle-like seed coat which changed from a light brown colour to a dark brown or black colour depending on the duration of storage. Such dark-brown or black coloured seeds exhibited enhanced germination capabilities. Germinated seeds when boiled, sustained a hard texture, bitter off-flavour and off-aroma when eaten from the uppermost region located near the embryo (Fig. 1h) (Mohammed and Wickham, 2011).

Storage under refrigerated conditions

Breadnut fruits are chilling sensitive if stored below 5-6ºC. The symptoms of chilling injury are manifested with the skin and spines having a dull green colour, water soaked flesh, browning of skin, flesh and seed, translucency of seed internal tissue, irregular brown coalesced sheet pitted lesions, invasive browning initiated at the seed perimeter and eventually penetrating into seed internal tissue, detrimental flavor changes, increased water loss and increased susceptibility to secondary infections (Mohammed and Wickham, 2003; 2016) (Fig. 1i-1k).

Mohammed and Wickham (2016) examined the combined effects of low temperature storage supplemented with modified atmosphere packaging (MAP) on the occurrence, manifestation and alleviation of chilling injury (CI) on breadnuts fruits. Whole fruits stored in paper bags at 4-5^{0}C displayed CI symptoms after 4 days. Severity of chilling injury symptoms became more pronounced when fruits were transferred to 20-22ºC for 1, 2, 3 days respectively. However, when fruits were individually sealed-packaged in low density polyethylene (LDPE) or high density polyethylene (HDPE) bags, visible evidence of chilling injury symptoms were not apparent until 8 days at 4-5ºC plus 2 days and more upon transfer to 20-22ºC. Perhaps, the saturated micro atmosphere created within the sealed bags as well as the prevalence of high relative humidity delayed the appearance of visible chilling injury symptoms. However, despite the apparent absence of chilling injury symptoms for fruits in sealed polyethylene bags, measurements of reduced bioelectrical resistance and increased electrolyte leakage indicated impairment to membrane integrity. The inverse relationship between lower bioelectrical resistance and higher electrolyte leakage indicated that these objective measurements could provide evidence of chilling injury prior to the appearance of visible chilling symptoms and could therefore be a useful early detection procedure on the occurrence of chilling injury (Mohammed and Wickham, 2003; 2016).

Pests and diseases

Breadnut fruits have few serious diseases or pests and low susceptibility to fruit rots caused by *Phytophthora, Colletotrichum (Anthracnose), and Rhizopus*. Because the breadnut begins to lose firmness very rapidly when stored under ambient conditions, the invasion of bacterial soft rot can be a problem. Physical damage during harvest and poor packaging can also facilitate and promote the proliferation of pathological agents. In addition, keeping the external skin under conditions where the RH is below 80% can encourage fungal growth. Breadnut fruits harvested too late or allowed to drop on the ground during harvesting operations would induce physical stress culminating in secondary infections and reduced marketability of fruits.

Processing and utilization

Fresh-cut technology

Enzymatic browning (Fig. 1e) is initiated on the flesh and seeds from fruits harvested at the horticultural stage of maturity (weeks 8-10 after fruit set) upon exposure to air when peeled, sliced or diced within 3 to 4 minutes. Peeling to remove the skin and cutting of flesh into several pieces must be done at 5-7ºC and the flesh must be dipped immediately under water or water plus vitamin C to minimize enzymatic browning. Fresh-cut slices should be stretched-wrapped in styrofoam trays and stored at 7-8ºC and 90-95% RH (Mohammed & Bridgemohan, 2020). Fresh-cut slices can be frozen, but if the flesh is stored together with the seeds the cooking quality is compromised (Bridgemohan and Mohammed, 2019).

Harnarine and Salick (2016), investigated the market opportunities and expansion for fresh-cut curried breadnut in West Indian cuisine, particularly at weddings and religious events where it is required in large quantities. Curried fresh-cut breadnut with an enhanced coconut milk flavour, is a popular side dish both locally and in the ethnic communities in foreign countries, namely, Canada, USA and England. However, the preparation of the fresh-cut fruit which involves separation of the flesh integuments is time consuming, labour intensive and tedious. Harnarine and Salick (2016), successfully tested the market potential for ready-to-cook fresh-cut breadnut and designed and built a machine that significantly reduced the time for preparation which manually required 1.5 hours per fruit to 5-6 minutes per fruit using their automated devise.

Waste recovery and utilization

Lim et. al (2017) investigated the uses of breadnut peel and core. Both by-products are inedible and discarded as waste products. However, their studies led to the development of a novel low-cost biosorbent for the removal of methylene blue (MB) adsorption. Moreover, they also reported that the biosorption process as being favourable and spontaneous with maximum adsorption capacity at 298 K, with heating not required to enhance its absorption capacity. Unlike other biosorbents which have to be activated to enhance biosorption capacity, the inedible waste from breadnut fruit required no-pre-treatment and was limited to oven drying only. Fast kinetics coupled with a high qmax made the breadnut waste products attractive, useful and beneficial in wastewater treatment as it would be more cost effective and energy efficient.

Chundawat et. al (2020), analyzed the huge potential for bioenergy obtained from waste to decrease the speed of global warming. Earlier, Olguin-Maciel et. al (2019), from the Natural Resources and Renewable Energy Unit of the Yucatan Scientific Research Center (CICY), Mexico, developed a new technique to produce bioethanol by fermenting breadnuts. They described a consolidated bioprocess (CBP) method that could be applied with breadnut flour when inoculated with a fungus to produce an enzymatic battery that unfolded the starch into free sugars, which simultaneously enabled the organism to ferment the sugars to produce bioethanol and generated additional value-added products during the process.

FUTURE RESEARCH NEEDS

Determination of the respiratory pattern of breadnut fruits are required. Antioxidants to minimize enzymatic browning of fresh-cut slices and postharvest treatments to reduce the dramatic changes in texture during ripening are also required for further investigations. Experiments to determine the effects of ethylene antagonists such as 1-MCP on quality and shelf life of breadnut fruits are warranted. The physiological and biochemical basis of chilling injury must also be explored.

Conflict of interest

The authors declare no conflict of interest.

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