Beyond the Bounty: Breadfruit (*Artocarpus altilis*) for food security and novel foods in the 21st Century

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Research

Abstract

The Food and Agriculture Organization recently reported that the number undernourished people has reached a record high of 1.02 billion, most prevalent in the tropics. Breadfruit, *Artocarpus altilis* (Parkinson) Fosberg, is an underutilized Oceanic staple crop long recognized for its potential to alleviate hunger in tropical climates. Breadfruit can be grown sustainably with minimal agricultural inputs and can be multicropped with high value cash crops such as coffee, pepper, or vanilla. A great diversity of cultivars with varying nutritional and agronomic characteristics exists, yet few cultivars are widely cultivated. Recent developments in micropropagation have made possible large scale propagation and dissemination but to fully utilize this resource, a deeper understanding of the nutritional characteristics, and the development of new products and markets are needed. This review will highlight and describe the state of our current knowledge and the potential for breadfruit as a sustainable crop to provide new foods for Western markets and food security for the growing global population.

Introduction

Food security was defined at the World Food Summit held in Rome, 1996, as “when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life” (World Bank 2007). During this meeting, representatives from 185 countries pledged to reduce world hunger to 50% of 1990-1992 levels by the year 2015. However, since this meeting there has been an unfortunate increase in hunger worldwide (FAO 2008) and the estimated number of undernourished people has increased to a record high of 1.02 billion, approximately 1 in 6 people (FAO 2009a). One of myriad factors responsible for this trend is the dramatic increase in food prices that occurred during the last decade. Since 2000, the overall food price index has increased 120%, led by an increase of 184% for cereals (FAO 2008). In addition to overall undernourishment, specific vitamin and mineral deficiencies are prevalent in many regions and represent a significant threat to food security. Seventy percent of the undernourished population live in the rural areas of developing nations and depend primarily on agriculture for their livelihood (World Bank 2007). As such, agricultural development must play a leading role in the alleviation of world hunger and to increase global food security.

Breadfruit (*Artocarpus altilis* Parkinson (Fosberg)) is a traditional staple crop grown for its starchy fruit throughout Oceania (Ragone 1997). Breadfruit yields of 6 t/ha (edible dry weight) have been reported (Sauerborn 2002). This is an impressive yield compared to the current predominant staple crops, with average yields of 4.11 t/ha for rice

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(2005), 4 t/ha of corn (1990-2000) and 2.6 t/ha of wheat (1990-2000) (Calpe 2007, FAO 2009c, d). Breadfruit is also a relatively low input crop and is a key component of some agroforestry systems (Fownes & Raynor 1993). Despite the high yields, potential for low input and sustainable production systems, breadfruit remains a marginal crop outside of the Pacific region (Ragone 1997). The millennia of selective breeding by the indigenous peoples of Oceania has resulted in enormous variability in morphological, agronomic, and nutritional characteristics among cultivated varieties (Zerega *et al*. 2004, 2006). Many of these cultivars are at risk of disappearing due to the loss of traditional indigenous knowledge, shifts in agricultural production , natural disasters and urban development. In this review the potential of breadfruit as a staple crop that has the potential to significantly improve global food security and help avert the significant food shortages that loom in the near future will be discussed.

Breadfruit: An Historical Perspective

While much of the temperate world may know breadfruit as an obscure plant seen on tropical vacations or in movies and books, the potential of this plant as a valuable food resource has long been recognized. The Spanish collected breadfruit and introduced it to the Philippines during the 17th century, but it was not until the 1700s that more widespread dissemination of the crop outside of Oceania occurred (Barrau 1976, Ragone 1997, Smith *et al*. 1992). This spread was spurred by the writings of Sir Joseph Banks who recommended the introduction of breadfruit to the Caribbean and other tropical colonies as a source of food after seeing it on his voyage on HMS Endeavour from 1768-1771 (Beaglehole 1962). After his failed attempt to introduce Tahitian breadfruit to the Caribbean following the famed mutiny on the HMS Bounty, Captain William Bligh led a subsequent expedition and successfully transported more than 600 breadfruit plants to Jamaica and St. Vincent in 1772 (Powell 1977, Ragone 1997). Soon after, French contemporaries introduced breadfruit to many of their tropical colonies. Breadfruit is now cultivated to a limited extent in over 80 countries worldwide including regions of Africa, Australia, South America, South and South-East Asia.

Breadfruit is a well known part of daily life in much of Oceania (Melanesia, Micronesia and Polynesia) where it has been cultivated as a staple crop for 2000-3000 years (Zerega *et al*. 2004, 2005) and plays a significant role in many aspects of daily life. There are many legends about the origin of breadfruit from various parts of Oceania (Ragone 1991) that often describe the origins of the breadfruit tree arising from a man or god, and providing sustenance during times of famine. The following example was originally recorded on Raiatea, based on an oral account in 1887 (Henry & Orsmond 1928, Ragone 1991):

> "During a time of famine long ago, red clay was the only food. A Raiatean man took his wife and four children into the mountains where they hid in a cave and ate ferns. He told his wife to go outside in the morning and she would see "my hands become leaves, the trunk and two branches my body, and the round fruit my head and the core inside, my tongue." In the morning, a beautiful tree stood as her husband had foretold. That valley is now called Tuauru, the place of breadfruit. She roasted the fruit, soaked it in a nearby stream and peeled it. She fed her family, but did not first make a customary offering to the king. When she prepared the fruit, pieces of the core and peel washed down stream. Servants of the king were catching shrimp in the stream. They found and ate the pieces. They were curious about this strange food and searched until they found the tree. They asked the woman what it was and she replied uru. She explained how it had arisen from the body of her husband who wanted to feed his family. The servants admired the tree which was covered with fruit of all the cultivars. The tree was taken down from the mountain and planted in her family's marae. A root was broken off and taken to the island of Tahaa where it grew. Ripe fruits were taken to the king and he liked it so much he ordered his servants to bring the tree and its owner to him. While they were transplanting the tree, woman begged for some roots and planted them in a valley which became known as Maiore. The family wept for their lost tree, but new trees soon arose from the roots left behind."

Throughout Oceania there are hundreds of unique cultivars of breadfruit exhibiting great diversity in many attributes (Morton 1987, Ragone 1997). For example, there are 132 cultivars documented from Vanuatu (Walter 1989), 70 from Fiji (Koroveibau 1967, Morton 1987), 50 from Pohnpei (Raynor & Fownes 1991, Ragone & Raynor 2009), more than 30 from Tahiti (Wilder 1928) and over 40 from Samoa (Ragone *et al*. 2004). Cultivars are named and valued based on morphological characteristics, cooking and storage qualities of the fruit, and agronomic characteristics. Cultivars in Samoa are generally named using a binomial system, composed of the generic name **`ulu**, the local name for breadfruit, followed by a specific epithet that often provides a description of the fruit or cultivar in general (Ragone *et al*. 2004). However, the general term **`ulu** is often not included for cultivars in which it is implicitly understood. For example, **Ma`afala**, the most commonly known cultivar in Samoa, is not typically referred to as **`ulu ma`afala**, but it is understood and may be referred to as such if needed (Ragone *et al*. 2004). A similar naming system is used in Pohnpei where the generic name for breadfruit is **mahi** and most cultivar names are binomials with **mei** or **mein** included as part of the name, e.g., **Meiuhpw** or **Meinpadahk**. Only a few names, such as **Lipet** or **Luhkual**, are monomials. Pohnpeians classify all breadfruit into two types based on skin texture: (I) smooth (**meiniwe**) or (II) rough (**meinsahrek**) (Ragone & Raynor 2009).

As indigenous peoples in Oceania are becoming more modernized and shifting away from traditional foods in exchange for imported crops, much of the information about cultivars and breadfruit in general is being lost; for example a 20-29 year old Samoan knows an average of 6.1 cultivars while a 60-69 year old Samoan knows an average of 9.2 (Ragone *et al*. 2004). Many other aspects of traditional knowledge such as cultivation and storage techniques are also threatened by cultural erosion (Lee *et al*. 2001, Ragone *et al*. 2004).

Often overshadowed by its value as a food crop, breadfruit has long been valued for a variety of medicinal and other secondary applications. The wood is used in the construction of homes and canoes, is prized for its resistance to termites, and is often used for wood carvings (Ragone 1991). The sticky latex has been used as birdlime, as an adhesive/caulking in canoes and in traditional medicine. The bast fibers were used for the production of cloth and cordage, with specific cultivars desirable due to the high-quality cloth that they produced. Various parts of the plant, including crushed leaves, latex, bark, and roots, have been used to treat a variety of ailments ranging from skin conditions to high blood pressure (Table 1). Recent research from Indonesia has reported the patenting of phytochemicals isolated from leaf tissue of bread-

Table 1. Traditional medicinal uses of breadfruit (*Artocarpus altilis* (Parkinson) Fosberg).

Location	Plant Part	Preparation	Use	Reference
Vanuatu	Latex	Mix equal amount of latex from *Ficus adenosperma* and *Artocarpus altilis* and drink	Menorrhagia	Bourdy & Walter 1992
Vanuatu (Mota Lava)	Latex	Not documented	Diarrhea	Navarro *et al*. 2007
Pacific Islands	Latex	Rubbed into skin	Broken bones and sciatica	Ragone 1997
Pacific Islands	Latex	Diluted and taken internally	Diarrhea, dysentry and stomach aches	Ragone 1997
Pacific Islands	Latex and/or crushed leaves	Rubbed into skin	Skin ailments and fungal infections	Ragone 1997
Pacific Islands	Latex and/or crushed leaves	Latex and/or juice from crushed leaves	Ear infections	Ragone 1997
Western Pacific	Leaf bud and latex	Chew and swallow from one to five fresh leaf buds, then drink one small glass of fresh latex. Repeat one to three times per day, until recovery is complete	Ciguatera poisoning	Bourdy *et al*. 1992
Western Pacific	Leaf Buds	Mix fresh leaf buds together with coconut oil	Ciguatera poisoning	Lobel 1979
Trinidad and Tobago	Leaves	Not documented	Hypertension	Lans 2006
Suriname	Leaves	Not documented	Fever	Bipat *et al*. 2008
Rotuma	Leaves	Not documented	Oral inflammation and pain	McClatchey 1993
Taiwan	Leaves	Not documented	Liver disease and fever	Ragone 1997
West Indies	Leaves	Tea made from yellowing leaves	High blood pressure, and perhaps diabetes	Ragone 1997
Vanuatu (Mota Lava)	Young leaves	Not documented	Headaches	Navarro *et al*. 2007
Vanuatu (Aneithyum)	Young leaves	Not documented	Urinary infections	Navarro *et al*. 2007
Vanuatu (Mota Lava)	Male inflorescence	Burned	Mosquito repellant	Navarro *et al*. 2007

Location	Plant Part	Preparation	Use	Reference
Not documented	Male inflorescence	Roasted, powdered and rubbed on gums	Aural pain relief	Ragone 1997
Not documented	Root	Not documented	Purgative	Ragone 1997
Not documented	Root	Mascerated and used as a poultice	Skin ailments	Ragone 1997
Western Pacific	Shoots	Fluid pressed from the shoots	Ciguatera poisoning	Weiner 1984
Samoa	Leaves	The juice from the chewed or crushed leaf petiole is dripped into the afflicted eye	Injured eyes	Whistler 2001
Samoa	Bark/root	An infusion from the scraped bark or roots is sometimes taken as a potion	Urinary tract problems	Whistler 2001
Samoa	Small branches	The smoke from a hollow, burning breadfruit twig is sometimes blown into the anal area of an infant for treating childhood ailments collectively called ila.	Ila	Whistler 2001
Vanuatu (Mota Lava)	Unknown	Not documented	Black magic, stop the rain	Navarro *et al*. 2007

fruit trees for the prevention of stroke and cardiovascular diseases (Sagita 2009). The use of breadfruit in medicine developed in traditional breadfruit growing regions in Oceania and was spread, or more likely developed independently, in areas where it is a relatively recent introduction such as the Caribbean and Taiwan (Lin *et al*. 1992, McIntoch & Manchew 1993). The widespread use of this plant species in medicine, the possible independent development of these practices in isolated regions, and more recent empirical evidence suggest validity in its value in traditional medicine and potential for modern drug discovery.

Ecological Requirements

Breadfruit is well adapted to the wet tropics, doing best at temperatures ranging from 21-32 °C with an annual rainfall of 1525-2540 mm and adequate drainage (Ragone 1997, 2006a). Cooler temperatures often result in low yields and increased plant mortality (Lebegin *et al*. 2007). Although breadfruit requires relatively high levels of rainfall, it can survive droughts of 3-4 months after the tree is established (Elevitch & Wilkinson 2000). Tolerance to soil salinity is known to vary among *A. altilis*, *A. mariannensis* and hybrid cultivars (Ragone 1997, 2006a, Ragone & Manner 2006). *Artocarpus mariannensis* is often found on small atolls and is reportedly more tolerant of soil salinity as well as salt spray from the ocean than *A. altilis*. However, this difference has not been quantitatively evaluated, nor have comparisons between *A. altilis* and *A. altilis* × *A. mariannensis* hybrids.

Taxonomy and Botanical Description

Breadfruit is a tropical tree in the genus *Artocarpus* in the Moraceae (mulberry/fig) family (Figure 1; (Fosberg 1960, Jarrett 1959)). The genus is comprised of approximately 50-60 species native to South/South-East Asia, and Australasia (Kanzaki *et al*. 1997, Zerega *et al*. 2004). It is sometimes further divided into two subgenera, *Artocarpus*, which includes breadfruit, and *Pseudojaca* (Kanzaki *et al*. 1997). The common name 'Breadfruit' typically refers to the species *Artocarpus altilis* (Parkinson) Fosberg, but is occasionally used in reference to *A. camansi* or *A. mariannensis*. *Artocarpus altilis* is classified as a 'cultigen', a domesticated species of plant that is not found in the wild, domesticated from breadnut (*A. camansi*) (Zerega *et al*. 2004, 2005). *Artocarpus camansi* is native to Papua New Guinea and potentially the Moluccas and Philippines (Coenan & Barrau 1961, Zerega *et al*. 2004). *Artocarpus mariannensis*, another closely related species, is native to the Mariana Islands and Palau. Physical characteristics and Amplified Fragment Length Polymorphism (AFLP) analyses suggest that many cultivars of breadfruit are interspecific hybrids of *A. altilis* × *A. mariannensis* (Fosberg 1960, Zerega *et al*. 2004, 2005). *Artocarpus altilis* × *A. mariannensis* hybrid cultivars are found throughout Micronesia, but are absent from Melanesia and Polynesia with the exception of a few recently introduced cultivars (Fosberg 1960, Zerega *et al*. 2004). The existence of hybrid cultivars was originally proposed by Fosberg and later supported based on human migration patterns (Fosberg 1960, Zerega *et al*. 2004) as well as morphological and molecular analysis (Zerega *et al*. 2005). Phylogenetic analysis based on morphological characteristics and molecular evidence demonstrated that the three species be-

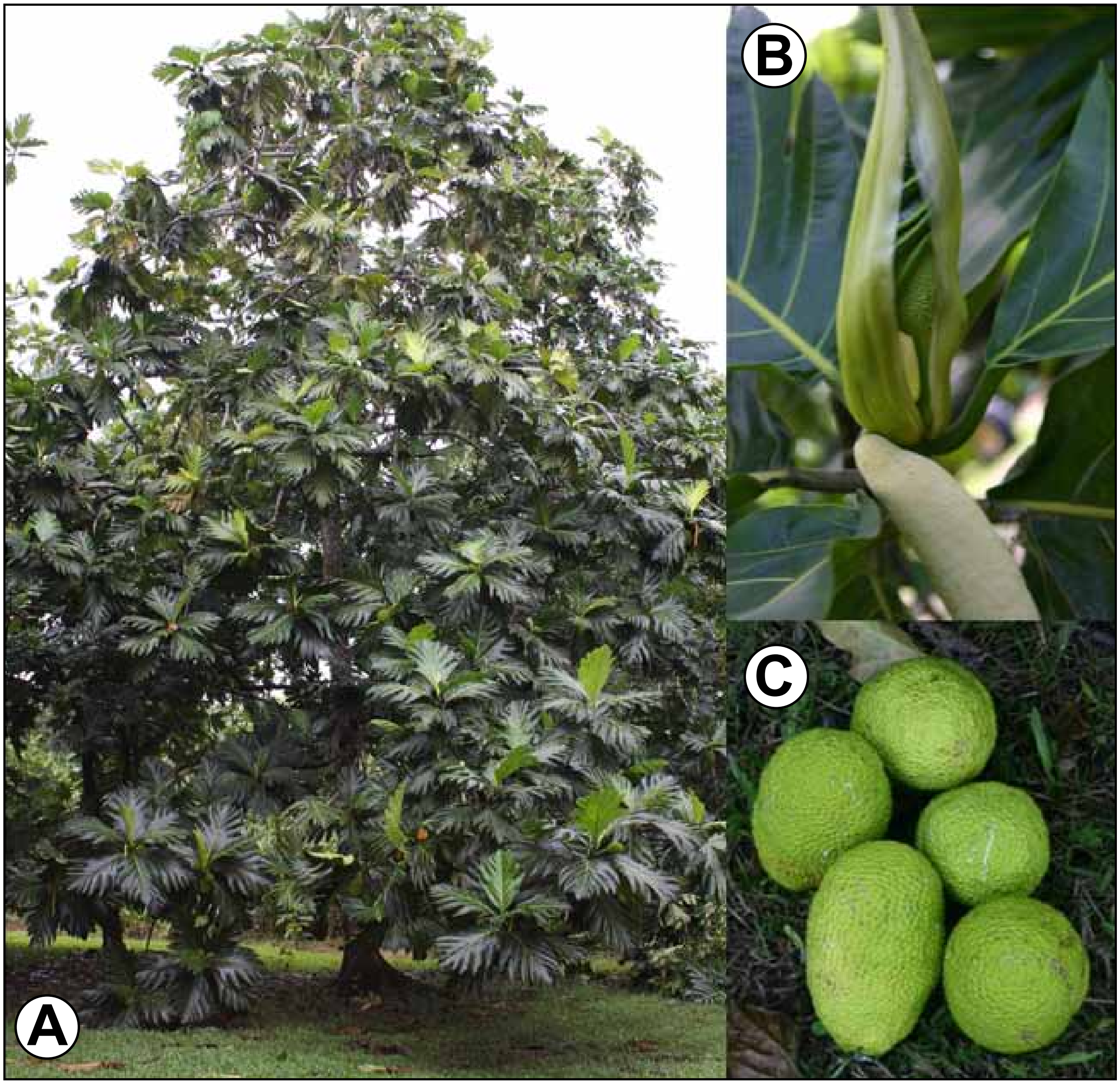

Figure 1. Morphology and growth of breadfruit (*Artocarpus altilis* (Parkinson) Fosberg trees. **A**. Trees grow from 30-60' tall and live for 35-50 years or longer when properly maintained. **B**. Male flower (bottom arrow) and fruit (top arrow) develop at the terminal apex of individual branches. **C**. Mature fruit are 1.0 - 3 kg in weight and exude a sticky white latex when first harvested.

long in a closely related monophylic group within the genus (Zerega *et al*. 2004, 2005, 2006).

Seeded varieties of breadfruit are commonly found in and around Papua New Guinea and throughout Melanesia, while seedless cultivars predominate in the Polynesian islands (Ragone 2001, Zerega *et al*. 2004). As human populations migrated throughout the Pacific islands, they developed and maintained their own unique cultivars. This has given rise to hundreds of distinct phenotypes often specific to individual islands. The distribution and development of these cultivars has been used to help elucidate human migration throughout Polynesia and Micronesia from Melanesia (Zerega *et al*. 2004).

Artocarpus altilis (Parkinson) Fosberg

Artocarpus altilis has previously been referred to as *A. incisus* (Thunb.) L.f. and *A. communis* J.R. Forst. & G. Forst., however, *A. altilis* is currently accepted (Fosberg

1941, 1960, Ragone 1997). *Artocarpus altilis* is a moderately large evergreen tree generally growing from 15-20 m, but sometimes reaching over 30 m tall (Niering 1963, Ragone 1997, 2006a). During development, terminal buds are encased by two large stipules up to 30 cm long that senesce as the buds emerge (Ragone 1997). Leaf morphology is highly variable between cultivars and to some degree even within an individual tree. The leaves are large, measuring between 22.8-90 cm long and 20-50 cm wide (Morton 1987, Zerega *et al*. 2005), are broadly obovate to broadly ovate in shape, and vary from almost entire to deeply lobed with pinnate venation (Ragone 1997). The abaxial surface of the leaf is often pubescent, with white or reddish-white trichomes found primarily along the veins. White latex is produced throughout the plant in mostly unarticulated laticifers, and is exuded upon mechanical injury (Harvey 1999).

Breadfruit trees are monoecious, with inflorescences comprised of about 1500-2000 individual florets connected to the receptacle (Figure 1B). Male inflorescences are elongated and club shaped, measuring 12.5-30 cm in length (Morton 1987, Ragone 2006a, Zerega *et al*. 2005). Female inflorescences are globose and develop into a multiple fruit referred to as a syncarp (Jarrett 1976). Male inflorescences appear earlier than female inflorescences providing a temporal separation preventing self pollination (Heard 1999, Sharma 1965). It is suspected that breadfruit is wind pollinated due to the reported lack of scent; however, some researchers have reported a distinct floral aroma (Heard 1999, Ragone 2006a). Additionally, bees have been observed visiting flowers and fruit, but their significance regarding pollination is not known (Brantjes 1981). Hand pollination of breadfruit inflorescences is sometimes done to improve fruit set (Heard 1999). As with leaves, fruit morphology displays a great diversity in size, shape and other attributes. Generally, fruit are about 12 cm long, 12-20 cm wide and weigh 1-2 kg, but some cultivars can produce fruit weighing up to 6 kg (Figure 1C; Ragone 1997, 2006a, Zerega *et al*. 2005). The skin varies in color from light green to yellow at maturity while the flesh can range from creamy white to yellow. The individual sections of the fruit surface can be relatively flat or conical rising up to 5 mm above the fruit surface. Thus, the fruit can be smooth, bumpy, or spiked (Ragone 2006a, Zerega *et al*. 2005). Many cultivars of *A. altilis* are triploid, and produce no seeds ($3n=2x=\sim84$) (Murch *et al*. 2007, Ragone 2001), while others are diploid ($2n=2x=\sim56$) and produce few to several seeds. *A. camansi* and *A. mariannensis* are both seeded diploids with $2n=2x=\sim56$ (Ragone 1997, 2001).

Artocarpus camansi Blanco

Artocarpus camansi, commonly referred to as seeded breadfruit or breadnut, resembles *A. altilis* to a large extent. Some of the distinguishing characteristics of breadnut are that the leaves are highly pubescent, covered in straight pale trichomes, the fruit contain numerous achenes (Bennett & Nozzolillo 1987, Roberts-Nkrumah 2002), and the fruit surface is covered in flexible spines measuring 5-12 mm (Ragone 2006d, Reeve 1974, Zerega *et al*. 2005). The principal difference is the high number of large, hard-coated seeds prevalent in the fruit. A key to differentiate these species has been developed (Zerega *et al*. 2005)

Artocarpus mariannensis Trécul

Artocarpus mariannensis, known as **dugdug**, **ebechei** and other common names in various regions is also similar to breadfruit in many respects, but can be distinguished using the aforementioned key (Ragone & Manner 2006, Zerega *et al*. 2005). Some of the distinguishing characteristics include entire leaf margins or 3-7 lobes in the distal third of the leaf, abundance of reddish brown trichomes on the midrib and abaxial veins, and the fruit is often irregularly shaped with dark green skin, even when ripe. Also, the individual fruit that comprise the syncarp are not fused except near the receptacle and near the skin (Ragone & Manner 2006). Distinguishing **dugdug** (*A. mariannensis*) from breadfruit (*A. altilis*) is relatively easy to the well-trained eye, however, *A. mariannensis* x *A. altilis* hybrids can display intermediate characteristics making their identification more complex (Fosberg 1960, Ragone & Manner 2006).

Genetic Diversity and Germplasm Conservation

Breadfruit is included as one of the 35 priority crops listed in the International Treaty on Plant Genetic Resources for Food and Agriculture for their potential impact on food security and food interdependence (FAO 2009b). Furthermore, The Global Crop Diversity Trust has developed a conservation strategy that identifies breadfruit as one of the high priority crops (Ragone 2007). Genetic diversity is greatest in Micronesia and Melanesia where seeded cultivars predominate, with less diversity found among the seedless triploid cultivars that typify the Polynesian cultivars (Ragone 2001, Zerega *et al*. 2005). However, despite the more limited genetic diversity within Polynesia, there is a high degree of morphological diversity and many distinct cultivars. The breadfruit trees introduced outside of Oceania are primarily derived from a select few seedless cultivars from eastern Polynesia and represent a very small amount of the existing diversity (Ragone 2007). Breadnut, *A. camansi*, has also been introduced outside of its native range and is cultivated on a small scale in the Caribbean, South America, South-East Asia and parts of Africa (Ragone 2006b). As with breadfruit, the introduced breadnut plants represent a very small amount of the genetic potential that exists. Little work has been conducted on cultivar development or comparison in breadnut (Ragone 2006b). Genetic diversity of breadfruit is manifested as phenotypic variation in leaf size and shape, seasonality of production, disease resistance, salinity tolerance, nutrient content, fruit size, shape, flavour, and texture. It is likely that breadfruit yields, nutrient content, shelf life and palatability could be improved with detailed descriptions and judicious selection of cultivars to be planted. It may also be possible to expand suitable breadfruit growing areas by identifying cultivars that display traits such as salinity and drought tolerance that would allow them to grow in traditionally marginal environments (Ragone 2007).

Oceanic societies have shifted away from subsisting on locally produced traditional crops, incorporating larger amounts of imported/introduced food such as rice and wheat (Englberger *et al*. 2007, Morton 1987, Ragone 2007). For example, between 2001-2003 wheat and rice accounted for approximately 20 percent of the average Samoan diet and 40 percent of the average Fijian diet (FAO 2007). This dramatic shift in dietary intake indicates a reduced emphasis on the cultivation and the subsequent *in-situ* conservation of the immense number of cultivars that exist. Breadfruit trees are also susceptible to natural phenomena such as hurricanes and droughts. With fewer trees being cultivated the probability of losing genetic diversity during a natural disaster increases significantly. Many cultivars are endemic to individual islands and relatively isolated events can represent tragic genetic and cultural erosion.

In order to preserve the genetic diversity of breadfruit, several *ex-situ* germplasm collections have been established (Ragone 2007). However, many of these collections lack proper cultivar identifications and some have diminished due to lack of funding and maintenance (Ragone 2007). The largest active germplasm collection is located in the Kahanu Garden, Hana, Hawai`i, managed by the Breadfruit Institute (BFI), of the National Tropical Botanical Gardens (NTBG). This collection is comprised of 265 trees representing about 120 well-documented cultivars. However, *ex-situ* germplasm collections remain vulnerable to natural disasters, disease, and other deleterious events (Murch *et al*. 2007, Shi *et al*. 2007). In order to add a measure of security to the NTBG collection and enable large scale cultivar dissemination, the collection is being replicated *in-vitro* (Murch *et al*. 2007, Shi *et al*. 2007). These efforts are complicated by the high rate of endophytic bacterial and fungal contamination in wild trees (Murch *et al*. 2007, Rouse-Miller & Duncan 2000, Tuia *et al*. 2007) and differential responses to inductive stimuli requiring optimized regeneration protocol for each cultivar (Shi *et al*. 2007). Despite these difficulties, 17 cultivars have been successfully incorporated into an *in-vitro* collection, with an additional 24 in the preliminary stages.

Breadfruit Phytochemistry

Plants produce a wide range of phytochemicals loosely defined as secondary metabolites, compounds not usually necessary for basic metabolism but often function to attract animals or prevent infection, parasitism and predation (Simpson & Ogorzaly 2000). The *Artocarpus* genus is known to produce a large number of secondary metabolites, and is specifically rich in phenylpropanoids such as flavonoids and flavones (Nomura *et al*. 1998). *Artocarpus altilis* (breadfruit) is no exception with over 130 compounds identified in various organs of the tree, more than 70 of which are derived from the phenylpropanoid pathway (Table 2). Many of the isolated compounds have been found to exhibit biological activity including inhibition of platelet aggregation, anti-bacterial, anti-fungal, inhibition of leukemia cells and as an anti-tumor agent (See Table 2). These data support the claim that the breadfruit tree may be an effective medicine with the potential to treat an assortment of medical conditions. Although some ethnobotanical information regarding traditional alternative uses of breadfruit exists (Navarro *et al*. 2007, Ragone 1997), the literature is vague regarding methods of preparation, the degree of cultivar specificity, and other details that may be required in order to successfully identify useful products/compounds.

Table 2. Identity and reported biological activity of compounds previously from breadfruit (*Artocarpus altilis* (Parkinson) Fosberg). Compound identities are presented as they appear in the original publications and may not comply with IUPAC principles of chemical nomenclature.

Compound	Plant Part	Reported Biological Activity	Reference
1,2-cyclohexanediol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
1-methylbutyl acetate	Fruit (cooked)		Iwaoka *et al*. 1994
1-octen-3-01	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
1-penten-3-01	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
2,3-butanediol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
20,40,5,7-tetrahydroxy-6-(3-methyl-2-butenyl)flavone	Fruit		Iwaoka *et al*. 1994
2-butanone	Fruit (fresh)		Iwaoka *et al*. 1994
2-cyclohexenol	Fruit (cooked)		Iwaoka *et al*. 1994
2-cyclohexenone	Fruit (fresh and cooked)		Iwaoka *et al*. 1994

Compound	Plant Part	Reported Biological Activity	Reference
2-ethenyl-2-butenal (tentative)	Fruit (cooked)		Iwaoka *et al*. 1994
2-geranyl-2’,3,4,4’-hydroxydihydrochalcone	Heart Wood	5a-Reductase inhibition	Shimizu *et al*. 2000
2-heptanol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
2-heptanone	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
2-methyl-4-pentenal	Fruit (fresh)		Iwaoka *et al*. 1994
2-methylbutyric acid	Fruit (fresh)		Iwaoka *et al*. 1994
2-pentanol	Fruit (fresh)		Iwaoka *et al*. 1994
2-pentanone	Fruit (fresh)		Iwaoka *et al*. 1994
3-cyclohexenol	Fruit (cooked)		Iwaoka *et al*. 1994
3-hexene-2,5-diol (tentative)	Fruit (cooked)		Iwaoka *et al*. 1994
3-hexene-2,5-diol (tentative)	Fruit (cooked)		Iwaoka *et al*. 1994
3-hydroxy-2-butanone	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
3β-acetoxyolean-12-en-11-one	Fruit		Amarasinghe *et al*. 2008
5-ethyl2(5H)-furanone	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
AC-3-1	Inflorescence		Nomura *et al*. 1998
AC-3-2	Inflorescence		Nomura *et al*. 1998
AC-3-3	Inflorescence		Nomura *et al*. 1998
AC-5-1	Inflorescence		Nomura *et al*. 1998
AC-5-2	Inflorescence		Nomura *et al*. 1998
Amyl alcohol	Fruit (cooked)		Iwaoka *et al*. 1994
Artocarpin	Unspecified		Hakim *et a*l. 2006
Artocarpin dichoromethane hemisolvate	Root Bark		Chantrapromma *et al*. 2007
Artochamins B	Root Cortex	Anti-platelet	Wang *et al*. 2006
Artochamins D	Root Cortex	Anti-platelet	Wang *et al*. 2006
Artocommunol CC	Root Cortex		Wang *et al*. 2006
Artoindonesianin B	Unspecified		Hakim *et al*. 2006
Artoindonesianin F	Unspecified		Hakim *et al*. 2006
Artomunoflavonone	Root Cortex		Wang *et al*. 2006
Artomunoisoxanthone	Root Cortex		Wang *et al*. 2006
Artomunoxanthentrione	Root Bark		Nomura *et al*. 1998
Artomunoxanthone	Root Bark		Nomura *et al*. 1998
Artomunoxanthotrione epoxide	Root Bark		Nomura *et al*. 1998
Artonin E	Unspecified	Arachidonate 5-lipoxygenase inhibition; Inhibit leukemia cells	Nomura *et al*. 1998
Artonin E	Unspecified		Hakim *et al*. 2006
Artonin F	Unspecified		Nomura *et al*. 1998
artonin V	Stem Bark		Nomura *et al*. 1998
Artonol A	Unspecified		Nomura *et al*. 1998
Artonol B	Unspecified		Nomura *et al*. 1998
Artonol B	Unspecified		Hakim *et al*. 2006

Compound	Plant Part	Reported Biological Activity	Reference
Artonol C	Unspecified		Nomura *et al*. 1998
Artonol D	Unspecified		Nomura *et al*. 1998
Artonol E	Unspecified		Nomura *et al*. 1998
Benzaldehyde	Fruit (cooked)		Iwaoka *et al*. 1994
Benzyl acetate	Fruit (cooked)		Iwaoka *et al*. 1994
Benzyl alcohol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Butanol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Butyric acid	Fruit (fresh)		Iwaoka *et al*. 1994
Chaplasin	Unspecified		Hakim *et al*. 2006
Chloroform	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Cinnamic alcohol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Cis-2-hexenal	Fruit (cooked)		Iwaoka *et al*. 1994
Cis-3-hexenol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Cis-3-hexenyl acetate	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Cycloaltilisin	Stem		Chen *et al*. 1993
Cycloaltilisin 6	Inflorescence Stipule		Patil *et al*. 2002
Cycloartenyl acetate	Fruit		Amarasinghe *et al*. 2008
Cycloartobiloxanthone	Unspecified		Hakim *et al*. 2006
Cycloartocarpin	Unspecified		Hakim *et al*. 2006
Cycloartomunin	Root Bark		Nomura *et al*. 1998
Cycloartomunoxanthone	Root Bark		Nomura *et al*. 1998
Cyclocommunin	Root Bark		Nomura *et al*. 1998
Cyclocommunol	Root Bark		Nomura *et al*. 1998
Cyclocomunomethonol	Root Cortex		Wang *et al*. 2006
Cyclohexyl benzene	Fruit (fresh)		Iwaoka *et al*. 1994
Cyclomorusin	Unspecified		Nomura *et al*. 1998
Cyclomulberrin	Unspecified		Nomura *et al*. 1998
Cyclopentanol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Cyclyaltilisin 7	Inflorescence Stipule		Patil *et al*. 2002
Diethylene glycol monoethyl ether	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Dihydroartomunoxanthone	Root Cortex	Anti-platelet	Wang *et al*. 2006
Dihydrocycloartomunin	Root Bark		Nomura *et al*. 1998
Dihydroisocycloartomunin	Root Bark		Nomura *et al*. 1998
Dimethylbenzenepropionic acid	Fruit (cooked)		Iwaoka *et al*. 1994
Engeletin	Unspecified		Nomura *et al*. 1998
Ethanol	Fruit (cooked)		Iwaoka *et al*. 1994
Ethyl 3-hydroxybutyrate	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Ethyl acetate	Fruit (cooked)		Iwaoka *et al*. 1994
Ethyl benzoate	Fruit (cooked)		Iwaoka *et al*. 1994
Ethyl butyrate	Fruit (fresh)		Iwaoka *et al*. 1994
Ethyl palmitate	Fruit (fresh)		Iwaoka *et al*. 1994

Compound	Plant Part	Reported Biological Activity	Reference
Friedelan-3-ol	Root Bark		Fun *et al*. 2007
Friedelin	Root Bark		Fun *et al*. 2007
Frutackin	Seeds	Chitin binding, anti-fungal	Trindade *et al*. 2006
Geranyl dihydrochalcones (9 structures)	Leaves		Wang *et al*. 2008
Hexanal	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Hexanoic acid	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Hexanol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Hexyl acetate	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Isoamyl alcohol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Isoartocarpesin	Fruit		Amarasinghe *et al*. 2008
Isocyclomorusin	Stem		Chen *et al*. 1993
Isocyclomuberrin	Stem		Chen *et al*. 1993
KB-2	Stem Bark	Inhibit leukemia cells	Nomura *et al*. 1998
Methyl acetate	Fruit (cooked)		Iwaoka *et al*. 1994
Moracin M	Fruit	Anti-fungal; anti-oxidant; cytotoxic; phytotoxic	Amarasinghe *et al*. 2008
Morusin	Stem Bark	Anti-tumour	Nomura *et al*. 1998; Hakim *et al*. 2006
Norartocarpanone	Fruit		Amarasinghe *et al*. 2008
Norartocarpetin	Fruit		Amarasinghe *et al*. 2008
Octanoic acid	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Oxyresveratrol	Fruit	Anti-fungal; anti-oxidant	Amarasinghe *et al*. 2008
Phenylpropyl alcohol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Prenylflavanoids (3 structures)	Unspecified		Lu *et al*. 2007
Sitosterol	Fruit		Amarasinghe *et al*. 2008
Sitosterol b-D-glucopyranoside	Fruit		Amarasinghe *et al*. 2008
Toluene	Fruit (cooked)		Iwaoka *et al*. 1994
Trans,trans-2,4-heptadienal	Fruit (fresh)		Iwaoka *et al*. 1994
Trans-2(or 4)-chlorocyclohexano1	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Trans-2-hexenal	Fruit (cooked)		Iwaoka *et al*. 1994
Trans-2-hexenol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Trans-2-pentenal	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Trans-3-hexenoic acid	Fruit (fresh)		Iwaoka *et al*. 1994
Trans-3-hexenol	Fruit (fresh and cooked)		Iwaoka *et al*. 1994
Vanillin	Fruit (cooked)		Iwaoka *et al*. 1994
y- hexalactone	Fruit (cooked)		Iwaoka *et al*. 1994
y –valerolactone	Fruit (fresh and cooked)		Iwaoka *et al*. 1994

Nutritional Composition

Breadfruit is most often eaten as a staple food due to the high level of carbohydrates found in the flesh of the fruit (Figure 2A; Morton 1987, Ragone 1997, Ragone & Cavaletto 2006, Wootton & Tumalii 1984). In addition to being a valuable source of carbohydrates, breadfruit is also high in fiber, some vitamins and minerals. The nutrient composition of breadfruit reported in the literature is highly variable and extensive studies of the many existing cultivars have not been conducted. For example, the reported protein content of the fresh fruit varies by almost four-fold, reported fat content varies by more than a factor of 20, and a similar trend is seen in most of the micronutrients (Table 3). This extreme variation in nutritional content may be a result of differences in the maturity of the fruit tested, production systems, environmental factors, inconsistent analytical methods, and cultivars tested (Englberger *et al*. 2003, Ragone & Cavaletto 2006, Wootton & Tumaalii 1984). There is a need to conduct a comprehensive survey of representative cultivars in a controlled manner to determine the degree of variability among cultivars and identify elite genotypes.

Breadfruit is most often consumed fresh, used as a starchy vegetable. One of the biggest limiting factors for large scale production and international trade is the perishable nature of the fruit. In typical conditions, the fruit will begin to deteriorate in approximately five days (Worrell *et al*. 2002). The shelf life of breadfruit can be extended up to 3-4 weeks using controlled atmosphere storage maintained at 16°C with 5% oxygen, 5% carbon dioxide (Sankat & Maharaj 2007). The use of controlled atmosphere storage has significant potential to aid in scaling up breadfruit production and export, but these facilities are currently not available to growers in many regions that cultivate the crop. Traditionally, many Oceanic societies preserve breadfruit through a process of pit fermentation (Atchley & Cox 1985); however, this has not spread into new areas and may not be readily incorporated into diverse international diets.

In order to increase the shelf-life of breadfruit and create a product that can be incorporated into a variety of diets, the production of flour is an ideal approach. Breadfruit flour has been successfully used in stiff porridges (Mayaki *et al*. 2003), infant formulas (Esparagoza & Tangonan 1993), extruded products (McHugh *et al*. 2007), bread (Ayodele & Oginni 2002, Esuoso & Bamiro 1995,

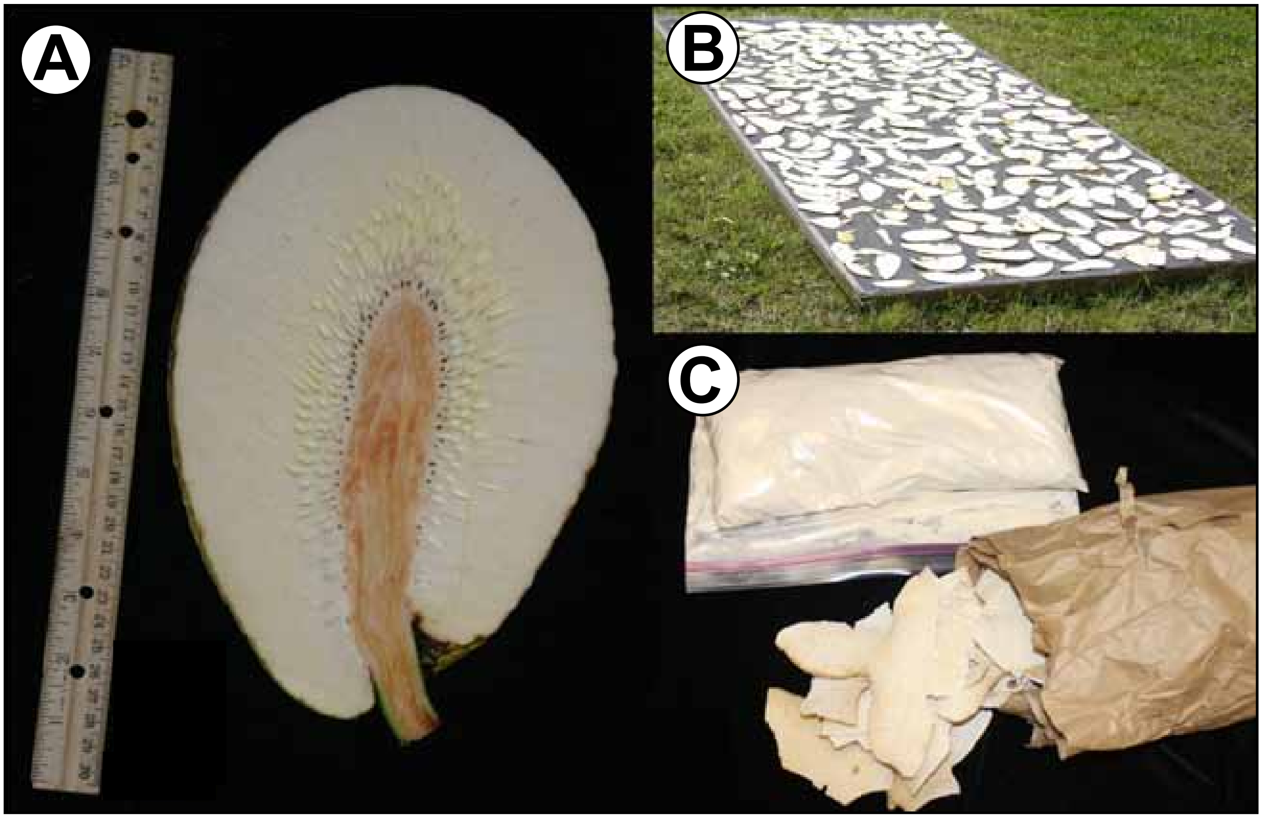

Figure 2. Preparation of flour from breadfruit (*Artocarpus altilis* (Parkinson) Fosberg). **A**. Mature fruit are peeled, halved and cored prior to slicing. **B**. Slices are dried on simple wire racks in sunlight or under a roof until fully dehydrated **C**. Dry slices can be ground into a fine powder using a variety of mills and burr grinders.

Table 3. Reported nutrient composition of breadfruit (*Artocarpus altilis* (Parkinson) Fosberg) mesocarp, mesocarp flour, fresh seed, and seed flour. ND = Not Detected, - = Not reported. Data compiled from (Englberger *et al*. 2003, Englberger *et al*. 2007, Huang *et al*. 2000, Mayaki *et al*. 2003, Morton 1987, Oshodi *et al*. 1999, Ragone 1997, Ragone & Cavaletto 2006, Webster 2006, Wootton & Tumaalii 1984).

	Fresh Fruit		**Breadfruit Flour**		**Fresh Seeds**		**Seed Flour (Dry/Flour)**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Moisture content (%)	62.7	89.16	2.55	21.02	35.08	61.9	8	8
kcal (per 100g)	105	138	-	-	-	-	-	-
Protein (%)	0.6	2.24	2.9	6.6	5.25	13.3	13.8	19.96
Fat (%)	0.1	2.36	1.8	2.8	2.5	5.59	3	12.79
Carbohydrates (%)	21.5	33	66.6	77.3	26.6	44.03	15.95	64.5
Starch (%)	20.1	20.1	53.4	75.7	-	-	-	-
Sugars (%)	2.9	2.9	2.17	31.8	-	-	-	-
Total fiber (%)	0.9	7.37	2.84	10.7	1.34	2.14	1.7	3.87
Soluble fiber (%)	ND	2.81	-	-	-	-	-	-
Minerals								
Ash (%)	0.56	1.2	1.69	4.5	1.5	5.58	3.42	3.5
Sodium (mg/100g)	1	70	-	-	ND	ND	0.29	0.29
Magnesium (mg/100g)	20	34	-	-	ND	ND	0.08	0.08
Phosphorous (mg/100g)	0.04	79	-	-	0.35	189	0.16	0.37
Potassium (mg/100g)	283	480	-	-	-	-	0.7	0.7
Calcium (mg/100g)	0.05	30	-	-	0.11	48.3	0.12	0.18
Iron (mg/100g)	0.29	2.4	-	-	2.3	3.87	-	-
Copper (mg/100g)	0.08	0.08	-	-	-	-	-	-
Boron (mg/100g)	0.52	0.52	-	-	-	-	-	-
Zinc (mg/100g)	0.07	0.13	-	-	-	-	-	-
Vitamins								
Vitamin B1 (mg/100g)	0.09	0.15	-	-	-	-	-	-
Vitamin B2 (mg/100g)	0.02	0.05	-	-	-	-	-	-
Vitamin B3 (mg/100g)	0.75	1.4	-	-	-	-	-	-
Vitamin C (mg/100g)	1.6	34.4	-	-	1.9	22.6	-	-
β-carotene (µg/100g)	ND	19.8	-	-	-	-	-	-
Retinol equivalents (µg/100g)	ND	157	-	-	-	-	-	-
Lutein (µg/100g)	38.6	119.7	-	-	-	-	-	-
Thiamin (mg/100g)	0.07	0.28	-	-	0.13	0.33	0.18	0.18
Riboflavin (mg/100g)	0.03	0.1	-	-	0.08	0.1	0.84	0.84
Niacin (mg/100g)	0.5	1.96	-	-	1.8	3.54	2.6	2.6

Nochera & Caldwell 1992), cake (Ayodele & Oginni 2002), pancakes (Ayodele & Oginni 2002) and biscuits (Nnam & Nwokocha, 2003, Olaoye *et al*. 2007, Omobuwajo 2003). For some items such as infant formulas, stiff porridges and extruded products, breadfruit flour was found to be ideal, and produced a high quality product (Esparagoza & Tangonan 1993, Mayaki *et al*. 2003, McHugh *et al*. 2007). In products where breadfruit was used in place of wheat flour, the quality of the products often suffers when a high proportion of breadfruit flour is used. This effect is most pronounced in traditional leavened wheat breads where products containing more than 10% breadfruit flour suffer from cracking and crumbling, but in some studies was still acceptable at rates of up to 30% (Ayodele & Oginni 2002, Esuoso & Bamiro 1995, Nochera & Caldwell 1992). In the production of biscuits, a higher level of breadfruit flour could be used, up to 67%, before product quality suffered (Nnam & Nwokocha 2003, Olaoye *et al*. 2007, Omobuwajo 2003). The differential performance of breadfruit flour relative to wheat flour is likely due to the intrinsic differences in their chemical and physical properties. In comparison to wheat flour, breadfruit flour is relatively high in total ash and crude fiber, but low in protein (Esuoso & Bamiro 1995, Olaoye *et al*. 2007). The relative mineral and vitamin profile is difficult to ascertain due to the high level of variation observed, and is likely dependent upon the cultivar used in the flour preparation. Although the bulk of research has been conducted on flour produced entirely from the fruit's flesh, the peel and core can be included during processing. Flour produced from whole fruit is higher in ash, fiber, protein, and has a higher bulk density than flour produced from just the fruit flesh (Adewusi *et al*. 1995, Mayaki *et al*. 2003). These differences are analogous to the production of whole wheat vs. refined wheat flours, and they may both find applications in the future.

Breadfruit has also been investigated as an alternative source of starch for industrial and pharmaceutical purposes. Seedless breadfruit cultivated in Venezuela yielded 18.5g/100g (DW) of starch (Rincón & Padilla 2004). The breadfruit starch exhibited higher levels of water absorption, solubility and swelling power than starch obtained from corn (*Zea mays* L.) or amaranth (*Amaranthus cruentus* L.). The gelatinization temperature of the starch was 73.3°C, and it was highly stable during heating and cooling cycles. Modification of the starch using oxidation, acetylation, annealing, or heat-moisture treatments can be used to alter some of these functional properties (Adebowale *et al*. 2005). In general, these modifications resulted in reduced gelling activity, solubility, pasting temperature, peak viscosity, hot paste viscosity and cold paste viscosity. Starch extracted from breadfruit has shown promising results in the pharmaceutical industry as an alternative to corn starch as a tablet binder (Adebayo & Itiola 2003) and tablet disintegrant (Adebayo *et al*. 2008). Breadfruit provides a ready alternative source of starch for a variety of industrial and pharmaceutical applications.

In addition to the starchy flesh, some cultivars also produce edible seeds. This is especially significant in breadnut (*A. camansi*), where the seed accounts for the bulk of the fruit and is the most commonly ingested portion. The breadnut seed is fairly high in carbohydrates, but contains significantly higher levels of fat and protein than breadfruit flesh (Table 2-1). Breadnut can also be used to produce flour, resulting in a product rich in protein, similar or higher than that found in wheat (Esuoso & Bamiro 1995; Oshodi *et al*. 1999). However, very few accessions have been studied to date and more work is required to evaluate the potential of the breadnut as a food resource (Ragone 1997).

Agronomic Considerations

Plant Propagation

Although some cultivars of breadfruit produce viable seeds, they do not survive desiccation and cannot be stored for long periods of time (Rowe-Dutton 1976, Zerega *et al*. 2004). Additionally, breadfruit is an out-crossing species and seeds do not grow true to type making seed propagation an undesirable method of propagation when a specific cultivar is desired (Ragone 2007). Traditionally, breadfruit is clonally propagated using root suckers, root cuttings, or air layering (Ragone 1997, 2006a). These methods are suitable for small scale local production, but are insufficient to meet the current global demand for planting material (Moustache & Moustache 2007, Roberts-Nkrumah 2007). Further, shipment of root cuttings between countries is not always practical as roots can carry fungi and bacteria that spread disease and specialized agricultural permits are often required, for example, breadfruit plants being imported into the U.S.A., Fiji, and Canada must be bare root, accompanied by a phytosanitary certificate and imported to a facility holding a valid Plant Protection permit. Many of the plants do not survive this type of shipment and losses of breadfruit propagules in this cross-border process are about 60% (Murch *et al*. 2008). As a result, the limited amount of modern distribution of breadfruit throughout the world that exists is a slow and cumbersome process.

Large-scale mass propagation using plant tissue culture provides an alternative method for the rapid, large-scale production of breadfruit plants in a sterile controlled environment (Figure 3; Murch *et al*. 2007, 2008). In brief, shoot tips and other small buds (Figure 3A) are surface sterilized to remove any fungi and bacteria (Figure 3B) before being cultured in a complete medium containing sugars, vitamins, minerals and a gelling agent (Figure 3C). Optimization of the type and concentration of plant growth regulators in the media induces the proliferation of shoots (Figure 3D) or roots (Figure 3E). Plantlets are subcultured into temporary immersion bioreactor vessels (Figure 3F) for the growth of entire plants about 10 cm tall in a sterile, controlled environment in about 6-8 weeks. These plantlets can then be shipped to destinations around the world or acclimatized to a soil environment for planting (Figure 3G). This process allows for production of thousands of plants that are almost identical clones of the original tree (Figure 3H,I). The sterile nature of this technique ensures that resulting propagules are free from insects and disease, reducing the risk to the grower, importation restrictions, and often eliminating the need for quarantine.

Acclimatization and Cultivation of Trees

Breadfruit cultivation is a time-honored tradition in much of Oceania. Young breadfruit trees are traditionally planted in small pits supplemented with compost; no further

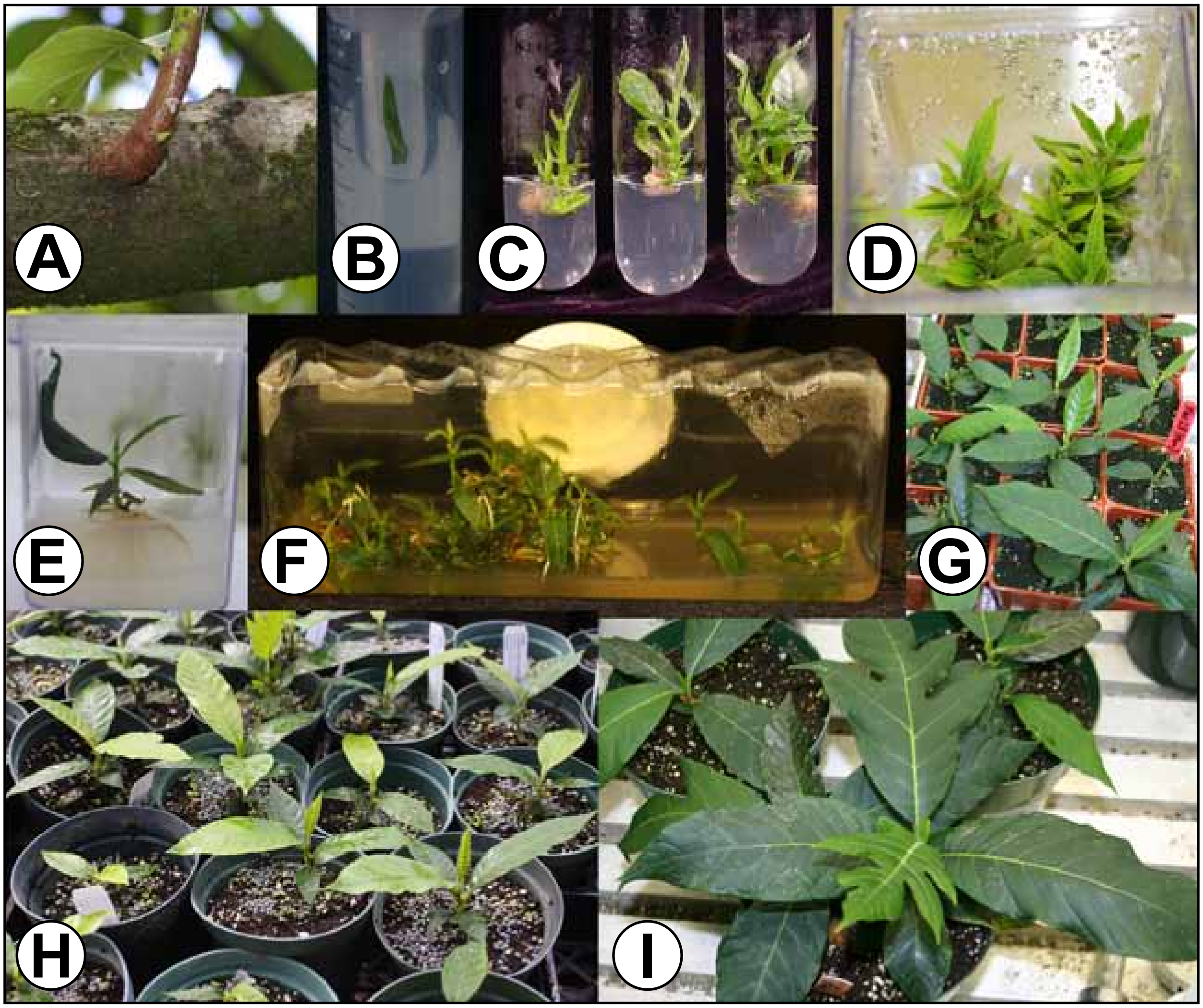

Figure 3. *In-vitro* production of breadfruit (*Artocarpus altilis* (Parkinson) Fosberg). **A**. Young buds from branches of mature trees provide the source materials for regeneration in tissue culture. **B**. Buds are disinfected of bacteria, fungi and other contaminants prior to culture onto a sterile media containing sugar, vitamins, minerals, a protein gelling agent and optimized concentrations of plant hormones. **C** Within 4 -6 weeks, multiple shoots develop on each of the sterile buds. **D**. Shoot proliferation continues for 3-4 months leading to a population of clones of the original plant in sterile tissue culture. **E**. Individual shoots are subcultured onto a rooting medium for development of roots and whole plants. **F**. Rooted plants can be grown to a height of 3-4 inches in sterile, controlled environment bioreactors. **G-I**. *In-vitro*-grown plants can be transferred to a growth cabinet or acclimatized in a greenhouse for production of mature plants suitable for distribution and planting the natural environment.

fertilization is used (Ragone 1997). They are planted during the rainy season to ensure adequate water for successful establishment. Breadfruit trees are a key component of various low input agroforestry systems (Elevitch & Wilkinson 2000, Raynor & Fownes 1991). Coconut trees are often used as the upper canopy, breadfruit trees are found in the lower canopy and smaller shrubs and herbaceous crops comprise the understory (Mueller-Dombois & Fosberg 1998). In other agroforestry systems, breadfruit is used as the upper canopy, with smaller crops grown underneath. Trees grown in agroforestry systems are generally spaced relatively far apart to accommodate the understory crops, which results in a lower yield than would be obtained using an intensive monoculture production system (Elevitch & Wilkinson 2000). Breadfruit grown in such a setting in Pohnpei produces yields in the range of 6.67 t/ha of fresh fruit (Raynor & Fownes 1991). Depending on the cultivar used and environmental conditions this would translate to approximately 0.5-1.9 t/ha of dried fruit flesh. The lower yield obtained in a mixed cropping system is compensated for by the additional harvest of spices, essential oil plants, fruit, roots/tubers, vegetables, herbs, coffee or other commodities grown in the understory. Understory crops, specifically annual and short lived perennials, are especially useful during the early establishment phase to provide income and/or food before the tree begins to bear fruit. Agroforestry also diversifies production and reduces the risk of catastrophic losses due to diseases or natural disasters that kill the tree crop. Breadfruit trees are also commonly found as “backyard trees” growing in the gardens of individual residences (Gbehounou 2007).

Modern Breadfruit Production

For better or worse, modern agriculture has shifted primarily to monoculture production systems. Although breadfruit is a major staple crop in many countries, large scale cultivation is virtually non-existent. The majority of breadfruit is still obtained from small growers, and consumed locally. Very little breadfruit is exported, with the Caribbean being a primary source, exporting around 1500 tons/year (Roberts-Nkrumah 2007). Some of the primary factors preventing large-scale production of breadfruit are the highly perishable nature of the fruit, lack of planting material, and a lack of marketing and distribution networks (Roberts-Nkrumah 2007).

Information on optimal fertilization regimes, pruning/training, planting density and other practices for modern orchard production have not been extensively evaluated, but there is some preliminary information (Coronel 1990, Goebel 2007, Lebegin *et al*. 2007, Webster 2006). Soil tillage, specifically deep tilling, has been conducted prior to orchard establishment (Lebegin *et al*. 2007). However, this is not traditionally required and may not be necessary in all locations and soil types. Likewise, fertilizer has been applied, but the nutrient requirements of the tree are not well known and application of fertilizer should be conducted based on a soil nutrient analysis. Planting densities ranging from 83.3-333 trees/ha have been used but even at 83.3 trees/ha the plants were too crowded upon maturity; lower planting densities have been recommended (Goebel 2007, Lebegin *et al*. 2007). The practice of planting sturdy trees such as *Syzygium* spp., *Casuarina* spp., and coconuts (*Cocos nucifera* (L.)) at the edge of the orchard has been recommended to minimize damage caused by high winds (Goebel 2007). To date, mechanical harvesters have not been utilized for the cultivation of breadfruit and hand harvesting remains the only viable option. It is estimated that over 50% of the fruit may be lost due to the difficulty of harvesting fruit from large trees (Roberts-Nkrumah 2007).

Yield Potential

The moisture content of the fruit ranges from 62.7-89% (Table 1) and individual trees produce between 50 and 900 fruit per season depending on environmental conditions, tree size and cultivar (Lorens & Englberger 2007, Marte 1986, Ragone 1997, 2006a). Fruit generally weigh 1-2 kg, but can reach up to 6 kg (Ragone 1997, 2006a, Ragone & Cavaletto 2006). The edible portion of the fruit accounts for approximately 70-75% of the fruit, with the skin and receptacle accounting for the remaining portion (Ragone 1997). Based on these factors the estimated yield of breadfruit ranges from 4 t/ha to 50 t/ha with edible dry weight yields of up to 14 t/ha. Bowers (1981) reported that 6 t/ha of edible dry matter production for breadfruit is a reasonable estimate (Sauerborn 2002). For perspective, the average global yield of irrigated modern rice is 4.1 t/ha with an estimated upper limit of approximately 10 t/ha using modern cultivars in intensive agricultural systems (Calpe 2007, FAO 1999).

The Potential of Breadfruit

Hunger is a problem that has ravaged human civilization since pre-history. With the current rate of population growth, food shortages are imminent unless dramatic increases in food production are achieved. Many of the countries that suffer from high levels of undernourishment are found in tropical climates that are suitable for breadfruit production. The significance of this is apparent when one compares the yield of breadfruit to other commonly grown staple crops such as rice, corn and wheat. Some cultivars of breadfruit also contain significant amounts of essential vitamins and minerals (Englberger *et al*. 2003, Ragone & Cavaletto 2007). Breadfruit offers an opportunity to significantly increase food production in regions of the world that need it the most in a sustainable manner, and could play a substantial role in averting a crisis.

In addition to its potential in fighting hunger, breadfruit has significant economic potential worldwide once the obstacles to developing a global market are overcome. With adequate product development and marketing, processed breadfruit could have huge potential value as a grain substitute, cattle feed, latex and lumber. The global market for grain is enormous. Projections for grain consumption estimate that 2.4 billion tons of grain will be consumed by 2015 with a value of approximately $600 billion (Bruinsma 2003). This is an average increase of 27 million tons ($7 billion) per year. As breadfruit emerges as a substitute for grain-based foods, the value of the worldwide breadfruit crop could easily reach billions of dollars in light of these economic trends.

Even in the absence of these trends, breadfruit would have significant growth potential in developed markets. Since the nutritional value of breadfruit flour has several advantages over cereal grains, an obvious application for the processed carbohydrate is as a nutritional supplement for products designed to appeal to the growing health conscious consumer group. A specific advantage of flour produced from breadfruit is that it is gluten free, giving breadfruit flour a unique market niche for those who suffer from Celiac disease and gluten allergies which affects approximately 1 in 133 people within the U.S. (Fasano *et al*. 2003). The market for gluten-free products in the U.S.

alone was approximately $700 million in 2007 and growing with a projected value of $1.7 billion by 2010 (Cureton 2007). Currently, gluten free products are considered expensive, presenting opportunity for gluten free flours such as breadfruit.

Breadfruit, and some of the by-products of breadfruit processing, can also be used as livestock feed (Ragone 1997). According to the National Corn Growers Association, over one half of all corn grown in the U.S. is fed to livestock within the U.S. and overseas (www.NCGA.com). With the price of corn reaching over $6 per bushel in 2008 (Tenenbaum 2008), the economic potential for an alternative livestock feed such as breadfruit is substantial. There are several secondary and tertiary products that may eventually develop from a global breadfruit market. Although the economic potential of these products may be less obvious than using breadfruit as a food source for people or livestock, examination of these possibilities reveals the true magnitude of breadfruit's global economic potential. These products are summarized below:

1. Ethanol. Ethanol can be made from breadfruit, by-products of breadfruit flour production, or from various parts of the tree (Ilori *et al*. 1996). In 2006, approximately 40 billion liters of ethanol biofuel was produced, utilizing about 50% of Brazil's sugarcane, and 20% of the American corn harvest (World Bank 2007). The demand for ethanol biofuel is increasing, and breadfruit could provide what appears to be an economically viable alternative feedstock (Ilori *et al*. 1996).
2. Latex. Latex derived from breadfruit has many traditional applications (Ragone 1997) and could find modern uses and be sold as a by-product. Since the latex can be harvested without detriment to the tree, this is complementary to production of food products.
3. Wood. Wood from breadfruit trees has been used locally for generations (Ragone 1997). It is resistant to moisture and pests, and performs well in furniture, boats, and other applications. Although harvesting the wood obviously cannot be a primary objective since it precludes fruit production, it is a possible source of additional income for growers as trees become less productive.
4. Carbon credits. Since the Kyoto protocol of 1997, capitalizing on carbon sequestration is as easy as selling carbon credits on the Chicago Climate Exchange (CCX), the European Climate Exchange (ECX) or the Global Carbon Exchange (GCX) (Capoor & Ambrosi 2008). Since breadfruit trees are proficient carbon sinks, and the breadfruit farming industry will directly address the ongoing deforestation problem in tropical regions, corporations in developed nations may use breadfruit as a way to offset their carbon emissions as cap-and-trade programs gain steam. This is a growing market and has grown from a value of $10 billion in 2005 to approximately $64 billion in 2007 (Capoor & Ambrosi 2008).

Overall, the economic impact of a global breadfruit market could be fundamental in helping less developed tropical nations improve their standard of living and per capita income. Currently, regions where breadfruit can be grown are among the poorest regions in the world. In addition, the tendency for these countries to import grains from developed nations like the U.S. exacerbates the cycle of poverty. By developing a global market for an environmentally sustainable crop, these regions would strengthen their positions in the global economy as well as improving economic conditions locally.

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