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Review Article

Adansonia Digitata (Baobab) Fruit Pulp as a Functional Ingredient for Space and Terrestrial Bone Health

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Abstract

Bone health is a critical concern on Earth and in space, where microgravity-induced bone demineralization poses serious health risks. Astronauts lose 1% to 2% of their bone mineral density per month in microgravity. This occurs because bones no longer need to support the body against gravity. On Earth, gravity exerts a continual mechanical load on the skeleton, helping bones maintain density and support the body. To prevent bone demineralization, functional foods high in calcium and bioactive substances are increasingly being investigated. This article reviews the nutritional composition, bioactive properties, and functional potential of baobab fruit pulp as a functional ingredient to promote bone health in both terrestrial and spaceflight contexts. Compositional findings indicate that baobab pulp is a carbohydrate-rich, micronutrient-dense plant matrix with moderate fiber and low lipid levels, characteristics increasingly recognized as important for bone metabolism via gut-bone and mineral bioavailability pathways. The significant mineral and phytochemical composition, with antioxidant and anti-inflammatory properties, makes baobab fruit a potential functional ingredient in terrestrial and space diets.

1. Introduction

The growth of bone demineralization during spaceflight and the growing bone health concerns on Earth indicate the need for nutrient-rich functional meals to restore bone integrity. Vitamin deficiencies and osteoporosis are still serious concerns for public health on Earth, especially in resource-deprived areas where a proper diet is not available. Similarly, dietary factors are important to long-duration space missions since bone mass is lost rapidly due to decreased mechanical strain, altered calcium metabolism, and oxidative stress in a microgravity environment. Fluid redistribution varies in microgravity [1], and movement in space is feasible. Vitamin deficiencies and osteoporosis continue to be serious public health problems internationally, particularly in resource-poor settings where access to nutritious meals is limited. Nutritional issues are especially. The immunological and cardiovascular systems deteriorate [2], the muscles of the arms and legs atrophy, and increased intracranial pressure leads to neurological and visual abnormalities [3]. Another result is that skeletal deconditioning due to microgravity exposure considerably increases the risk of fractures and osteoporosis, threatening extended-duration missions and astronauts' mobility upon return to Earth [4, 5]. Bones transmit forces from muscles to bear the weight of the body and are adapted to mechanical demands [6]. Spaceflight has effects similar to those of immobility and ageing on Earth, some of which may be permanent. Thus, reversing bone loss due to mechanical unloading or disuse remains a serious medical challenge in space and on Earth. Pharmacological therapies, like anti-resorptive bisphosphonates, minimize bone loss but may interfere with the gradual and sometimes imperfect post-flight healing [7]. Existing countermeasures for bone demineralization include exercise and supplementation. But long-duration missions will require nutrient-dense, shelf-stable diets. Space flight studies have enabled the development of integrated deconditioning and ageing therapies,

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including pharmacological, physical, and dietary approaches. Nutrition is a significant factor in bone remodeling, and calcium, antioxidants, and anti-inflammatory substances are important factors.

Adansonia digitata (Baobab tree) is a native African tree, and the fruit pulp is commonly used in traditional diets. It is commonly called "Kuka" in Hausa and is highly prized for its nutritious leaves and fruit, which are added to local cuisine and traditional medicine. Its unique nutritional profile and lengthy shelf life make it very attractive for terrestrial nutrition and space food systems. The fruit (as seen in Figure 2 below) is an important ingredient for making sauces or for use in local brewing (as it readily dissolves in milk and water) [8]. Some use it as an appetizer and a beverage due to its high levels of vitamin C, calcium, phosphate, fiber, potassium, and carbs [9]. The fruit pulp (as reported by Abdulwaliyu [10]) contains higher concentrations of vitamin C than oranges, with quantitative analyses revealing calcium concentrations of approximately 375–500 mg/100 g and vitamin C concentrations of more than 150 mg/100 g, which indicates its potential contribution to bone mineralization and collagen synthesis [10]. The baobab fruit contains higher levels of macronutrients than most food crops, increasing its value in international markets [11]. Thus, the exports of pulp to the European Union and the United States of America (USA) have increased. [12]. Baobab has been proven to have numerous components that decrease the risk of anemia, diabetes, cancer, hypertension, and other illnesses [10].

Vitamin C is a vital factor in the synthesis of collagen, a major predictor of the quality of the bone matrix, while calcium is the main structural element of the bone. Baobab's rich antioxidant components have the potential to combat reactive oxygen species that activate osteoclasts and bone loss. Baobab is underutilized in clinical nutrition and space health studies despite its rich nutritional content and traditional usage throughout Africa. Exploring fruit pulp as a functional ingredient is a novel, sustainable, and culturally relevant pathway to support bone health in astronauts and terrestrial populations. Adding this food to dietary regimens could perhaps help counteract global nutritional deficiencies and prevent bone loss during spaceflight, as demonstrated in Figure 1 below.

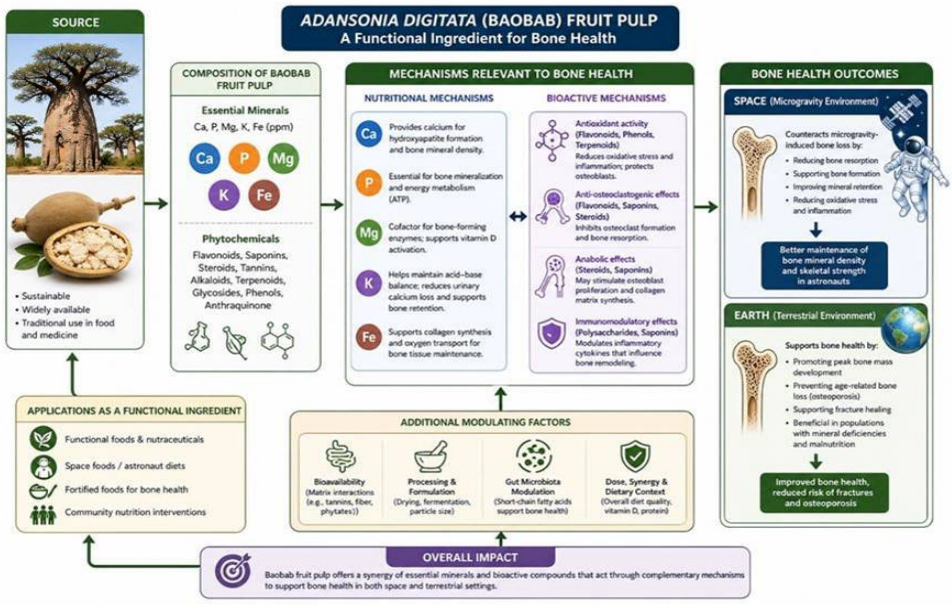

Figure 1: Conceptual Framework of the relevance of Baobab fruit pulp to bone health

2. Botanical and ethnopharmacological overview

Figure 2: View of a cracked *Adansonia digitata* fruit

Adansonia digitata is the most widely distributed species of the genus Adansonia, found in Africa and in the southern Arabian Peninsula (Yemen, Oman). Due to its nutritional and therapeutic importance, the tree is often referred to as the "Tree of Life". They are widely distributed in the hot, arid savannas of Sub-Saharan Africa, where they are the dominant trees in the landscape and make a watercourse apparent from a distance. Adansonia bears large, globose, indehiscent fruits with a woody outer shell, up to 25 cm (10 in) long. The fruit of the African baobab comes in a variety of shapes, from virtually round to cylindrical. The flesh inside the shell is light beige, juicy, and citrus flavored [13]. The seeds have a long dormancy period and only germinate after exposure to fire or passage through the animal gut [14].

The edible fruit [15] has been suggested to promote sustainable land care, raise food security, improve nutrition, and support rural development [16]. In Sudan, the dry pulp of the fruit is soaked and dissolved in water to form a juice known locally as tabaldi or gunguleiz [17]. Consequently, in 2008, the European Union approved the consumption and usage of the baobab fruit. It is widely used in smoothies, cereal bars, drinks, porridge, and fermented items.

3. Methods

A search for articles on the health benefits of baobab fruit pulp was conducted in various databases, including PubMed, Google Scholar, grey literature, and African Journals Online. The search technique included literature associated with baobab fruit pulp, bone health, terrestrial bone health, and space bone health. We employed a wide range of keywords, including "nutritional and health benefits of baobab fruit pulp", "nutrient content of baobab fruit pulp", "antioxidant potentials of baobab fruit pulp", "baobab fruit pulp and bone health", and "baobab fruit pulp and antimicrobial properties".

4. Results and Discussion

4.1. Micronutrients in Baobab fruit pulp

The composition of macronutrients found in Baobab fruit pulp, as demonstrated by different studies, is highlighted in Table 1 below.

Table 1: Proximate composition of baobab fruit pulp samples from selected studies (%)

Moisture (%)	Ash (%)	Fat (%)	Crude Fiber (%)	Crude Protein (%)	Carbohydrate (%)	Source
11.20 ± 0.20	4.50 ± 0.10	0.40 ± 0.10	6.10 ± 0.10	3.50 ± 0.10	74.30 ± 0.10	Oyeleke et al., 2012 [18]
12.27 ± 0.20	6.38 ± 0.52	0.70 ± 0.22	20.62 ± 1.24	3.76 ± 0.44	70.74 ± 0.49	Chabite et al., 2019 [19]
10.20 ± 0.30	7.69 ± 0.29	0.40 ± 0.00	5.70 ± 0.30	2.16 ± 0.03	73.87 ± 0.00	Adebisi et al., 2012 [20]
7.47 ± 0.01	4.10 ± 0.10	—	4.16 ± 0.07	1.23 ± 0.04	82.84 ± 0.01	Affo & Akande, 2011 [21]
12.95 ±0.04	8.0 ± 0.1	0.4 ± 0.1	52.0 ± 1.0	2.3 ± 0.1	37.0 ± 1.0	Vinha, et al., 2024 [22]

The proximate carbohydrate concentrations of the fruit pulps in the analyzed studies ranged from 70.74% to 82.84%, with the predominant component being carbs. All the analyzed studies had ash contents in the same range. The low crude protein and fat contents emphasize their small contribution to protein and lipid intake. Crude fiber levels were highly variable between experiments. The discrepancy may be attributed to the difference in sample source, processing protocols, or testing methods. This macronutrient review indicates that baobab pulp is not a primary protein source but can be an energy-dense functional addition. This is crucial for bone health because dietary carbohydrate indirectly controls calcium absorption by modifying intestinal fermentation and short-chain fatty acid production, both of which enhance mineral uptake in the colon. The fiber concentration was very variable among experiments, perhaps due to differences in environment and processing. High dietary fiber levels are linked to bone health via the gut microbiome axis, where fermentation products improve calcium and magnesium absorption while decreasing systemic inflammation, all of which are essential for regulating bone resorption. Low moisture content is especially important in space nutrition systems, where microbiological stability, mass efficiency, and storage time are critical requirements. The low-fat content seen in the research further enhances oxidant stability during prolonged storage, rendering baobab pulp ideal for spaceflight food system requirements where lipid oxidation is a major limitation.

4.2. Macronutrients in Baobab fruit pulp

The review identified five major macronutrients in Baobab fruit pulp across different studies. Their compositions are shown in Table 2 below.

Table 2: Mineral Composition of baobab fruit pulp samples from selected studies (ppm)

Source	Na (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	P (ppm)	Fe (ppm)
Oyeleke et al., 2012 [18]	35.10 ± 0.50	1410.35 ± 0.25	69.12 ± 0.02	78.18 ± 0.15	105.20 ± 0.10	5.85 ± 0.20
Chabite et al., 2019 [19]	1898.52 ± 291.28	1951.00 ± 234.30	—	2600 ± 100	2600 ± 800	3.50 ± 1.13
Adebisi et al., 2012 [20]	—	—	46.27	3.2	—	0.77
Affo & Akande, 2011 [21]	360	1890	1257	555	4.4	17.1
Silva, et al., 2023 [23]	34.61± 0.3	1240 ± 40	155 ± 2	309 ± 1	775 ± 2	14.97 ± 0.06

The levels of Sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), phosphorus (P), and iron (Fe) varied considerably between the studies. Most studies consistently identified potassium in high concentrations. Sodium levels were also variable, ranging from 35.10 $\pm$ 0.50 ppm to 1898.52 $\pm$ 291.28 ppm, indicating that sample composition or analytical conditions were significantly different across the reviewed studies. Magnesium concentrations were highly variable, with the greatest values reported by Affo & Akande [21]. Calcium and phosphorus are needed for the formation of hydroxyapatite in bone tissue [24], and magnesium inhibits the action of parathyroid hormone and vitamin D

metabolism [25]. From a physiological standpoint, potassium's prevalence in baobab pulp is significant in microgravity and on Earth as it reduces urinary calcium excretion and preserves skeletal calcium stores [26]. This is relevant for microgravity, where skeletal unloading is known to induce bone resorption and calcium loss. The presence of iron and trace minerals also improves hematological health, which indirectly affects bone remodeling through osteoblast activity dependent on oxygen transport and energy metabolism.

4.3. Phytochemical composition of Baobab fruit pulp

Table 3 highlights the phytochemicals found in Baobab fruit pulp from different studies.

Table 3: Phytochemical composition of Baobab fruit pulp

S/No	Phytochemicals	Source
1	Tannins	[20, 27]
2	Flavonoids	[20, 27, 28]
3	Alkaloids	[20, 28]
4	Steroids	[20, 27, 28]
5	Glycosides	[27]
6	Saponins	[20, 27, 28]
7	Phenols	[27]
8	Terpenoids	[27, 28]
9	Anthraquinone	[27]
10	Vitamin C/Ascorbic acid	[19, 22, 29–31]

Phytochemical screening revealed several bioactive compounds, including flavonoids, tannins, saponins, alkaloids, steroids, phenols, glycosides, and terpenoids [20, 27, 28]. The anti-inflammatory and antioxidant effects of these chemicals are particularly relevant to bone biology. Flavonoids have been reported to promote osteoblast development and inhibit osteoclastogenesis through the modulation of RANK/RANKL signaling pathways. Similarly, saponins and polyphenols are known to reduce oxidative stress, which causes bone loss in both ageing populations and astronauts. The phytochemicals and antioxidants present in baobab pulp suggest the fruit's potential in preventing oxidative stress and systemic inflammation (both of which are major contributors to bone demineralization). The synergy between polyphenols and minerals may boost mineral bioavailability through chelation and increased gastrointestinal absorption, although more in vivo evidence under microgravity simulation is required. The fiber-mineral-phytochemical matrix may potentially decrease oxidative stress and enhance gut-mediated mineral absorption, both of which are key to preventing osteoporosis. The stability, nutrient density, and antioxidant potentials of baobab fruit pulp suggest it is a desirable ingredient for shelf-stable functional foods aimed at slowing bone loss.

5. Summary

The mineral content of baobab fruit pulp suggests the relevance of its inclusion in diets for optimal bone health. Potassium (K) concentrations were consistently high, while calcium (Ca), phosphorus (P), and magnesium (Mg) were present in different but physiologically relevant proportions throughout the research analyzed. These minerals have complementary activities in bone metabolism. Calcium and phosphorus are required for the formation of hydroxyapatite, while magnesium is a cofactor in enzymatic pathways involved in bone remodeling and vitamin D activation. The high potassium content is particularly essential since potassium-rich diets are reported to inhibit bone resorption by changing systemic acid-base balance. Vitamin C and organic acids are examples of boosting agents that affect calcium bioavailability. Baobab is also rich in vitamin C, which may increase mineral absorption. Studies have indicated that iron bioavailability improved with the consumption of baobab. The baobab pulp also has excellent antioxidant potential due to its high level of polyphenols and vitamin C. It is known that antioxidants aid in reducing oxidative stress that contributes to bone resorption and osteoclast activation. Studies confirm that baobab has bioactive chemicals with antioxidant activity at least equal to popular fruits [30]. Baobab contains polyphenols like epicatechin and procyanidins that are anti-inflammatory [30, 32], potentially lowering cytokine-driven bone deterioration. Though clinical evidence is sparse, the combination of calcium, antioxidants, and anti-inflammatory substances suggests that baobab may enhance osteoblast activity (bone formation) and inhibit osteoclast-mediated bone resorption.

6. Conclusion

The fruit pulp of *Adansonia digitata* is a nutrient-rich functional ingredient with high levels of calcium, vitamin C, polyphenols, phosphorus, carbohydrates, and soluble and insoluble fibers. This has led to global demand for the plant across several industries, including food, cosmetics, and medicine. In many parts of Africa and Europe, the whole plant is used for various medicinal purposes. Its antioxidant and anti-inflammatory properties, combined with its high mineral content, make it a good choice for promoting bone health in terrestrial and space environments. The pulp can be used in functional drinks, high-nutritional-density energy bars, powdered supplements, and enriched staple foods. The fruit dries naturally in its shell, resulting in low moisture content and a long shelf life. This makes it ideal for space missions, where shelf life is crucial, weight and bulk must be minimized, and nutrient density is emphasized. Its natural stability and adaptability also make it suitable for space nutrition systems.

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