

Review Article**An insight into the molecules and materials of the haustorium of the Asian Palmyra Palm (*Borassus flabellifer*) and their nutraceutical values**

Sweetey Angela Kuldeep¹, Vidhyashini Vijayakumar¹, Showmiya Segaruban¹, Yunitha Sinnathurai¹,
Mohammed Saium Hossain², Kohinoor Begum², Jefwin Paul^{3,4}, Paulraj Mosae Selvakumar^{1,*}

¹ Science and Math Program, Environmental Science Program, Asian University for Women, Chattogram 4000, Bangladesh

² Bangladesh Sugar Crop Research Institute, Ishwardi, Pabna 6600, Bangladesh

³ Panaiyaanmai(Palmyraculture)—The Centre for Self-Reliance and Sustainable Development, Munnnetram Green Industry, Kadayam, Tamil Nadu 627423, India

⁴ Punitha Arulappan Hr. Sec. School, Avudayanoor, Tamil Nadu 627808, India

* Corresponding author: Paulraj Mosae Selvakumar, p.selvakumar@auw.edu.bd

Abstract: The *B. flabellifer* L. has untapped potential in sustainable development and its products have many high food and medicinal values. Palmyraculture is defined as the plantation and utilization of Palmyra palm for self-reliance and sustainable development. The endosperm/embryo of germinated seeds is an important biomaterial, also known as haustorium. This paper provides comprehensive insights into the molecules of the haustorium, especially those of pharmaceutical and nutritional interests, and briefly explores other applications of haustoria. The discussions of seed germination, and consequently, the haustorium development have made their way in 21st-century research. With further advancements in chemical analytic techniques and the growing realization of diverse uses of nearly every part of the plant, more attention has been attracted to the phytochemical composition of the parts, including the haustorium. The recent research on the haustorium examines haustoria molecules, their respective functions and uses, and their interactions with external factors. During the period when the haustorium converts complex nutrients in the endosperm into simple forms for the growing embryo, it is composed of varying essential sugars, amino acids, phytochemicals, bioactive compounds, macro, and micronutrients, all of which are highly beneficial for human health. It also possesses glycosides, flavonoids, phenols, and saponins, which contribute to its medicinal properties of acting against hypertension, hypercholesterolemia, hyperglycemia, obesity, as anti-allergic, anticancer, and anti-neoplastic agents, and for fighting against oxidative stress. The most recent study on the haustorium highlights how its extracts serve as an efficient antioxidant and anti-inflammatory functional food. Future studies of the Palmyra palm haustorium could offer potential applications; emphasizing the pharmaceutical, nutritional, and ethnobotanical significance.

Keywords: palmyraculture; Asian Palmyra; *Borassus flabellifer*; haustorium; nutraceutical; bio-material

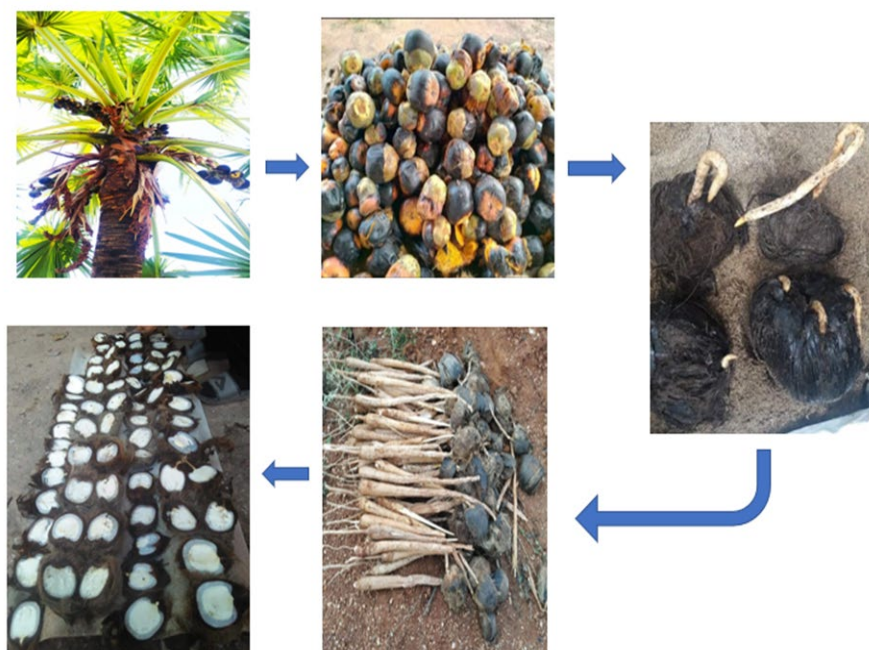
1. Introduction

Palms are monocot perennial angiosperms and are featured by their single-leaf type and woody stems, among the vast palm family of Arecaceae, Palmae, which boasts over 2400 species, the *Borassus flabellifer* Linn., commonly known as the Asian Palmyra Palm holds a special place. This palm tree is distinctive and thrives in tropical wet regions and has emerged as an economically beneficial and significant palm tree by serving as an important horticulture crop^[1-3]. While the natural distribution of the Palmyra palm is difficult to identify, primarily because of various anthropogenic activities, it is predominantly found in Cambodia, India, Indonesia, Sri Lanka, Thailand, and Vietnam. The *B. flabellifer* L. carries untapped potential in the sustainable development of countries as it creates opportunities for self-sustaining environmentally friendly lives.

Plantation and utilization of Palmyra palm for self-reliance and sustainable development is called palmyraculture^[4,5]. Palmyra products have many nutritive and nutraceutical values to enhance human life, and they also provide raw materials for goods and construction materials^[6]. Due to the presence of several bioactive chemicals, the palmyra tree's various components, including the roots, stem, flower, fruit, sprout, spadix, and seed embryo, have strong anti-inflammatory, antioxidant, antibacterial, anti-diabetic, and anti-diuretic properties^[7].

The Palmyra palm is also making its way into the field of nanotechnology, where it provides a sustainable source for the environmentally friendly synthesis of a wide range of nanomaterials, including gold, silver, zinc oxide, and bimetallic NPs, as well as nanocomposites, nanofilms, and nano-fibrillated cellulose. It offers a variety of applications in the field of nanomedicine too^[8,9]. Furthermore, it has paved the way for chemosensing. A variety of distinct chemical compounds with various functional groups has been found in the extract of palm fruit. There is a fluorescence emission towards Cd^{2+} and Fe^{2+} ions, which is attributed to the integrated binding sites found in the compounds of palm fruit. It was discovered that the fruit extract from the Palmyra palm functions as a turn-on fluorescence sensor to detect Fe^{2+} ions sensitively and selectively^[10].

Within the diversity of uses of Palmyra palm products, its embryo/crunchy kernel of germinated seeds, also known as haustorium, holds major significance. It is one of the most nutritious and tasty materials derived from palmyrah, called thavun in Tamil. The formation of haustoria as shown in **Scheme 1** and **Figure 1(a),(b)** are the focus of extensive research due to its therapeutic and nutritive properties, attracting palm researchers worldwide.



Scheme 1. Formation of Palmyrah haustorium.

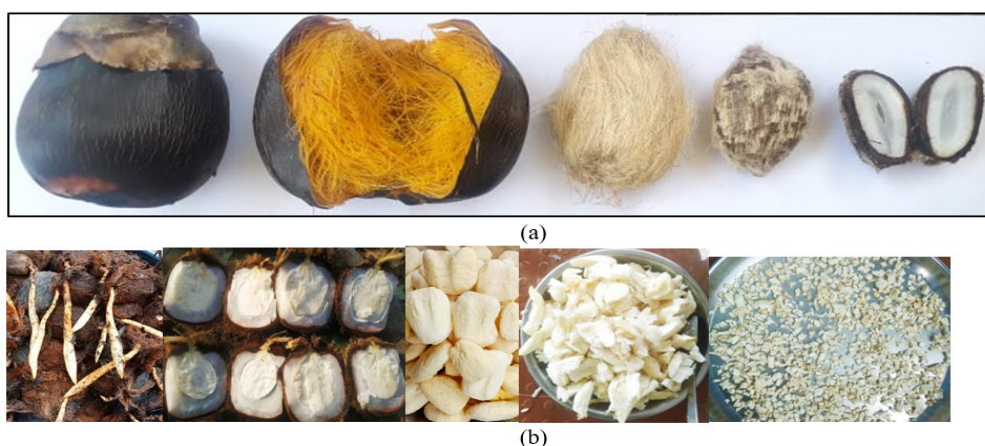


Figure 1. (a): Palmyrah Palm fruit, fiber, fresh seed, and the cross-section view of the seed. **(b):** Germinated Palmyra Seed cut open to represent a white spongy haustorium/seed embryo.

Source: Panaiyaanmai (palmyraculture)—the Centre for Self-reliance and Sustainable Development, Kadayam, Tenkasi, Tamil Nadu, India.

As with any product and part of the Asian Palmyra Palm, the haustorium also has therapeutic and nutritive properties. It has, thus, been the subject of research among palm researchers worldwide. Therefore, by first providing a history of the development of Palmyra palm haustorium research, this paper provides comprehensive insights into the molecules of the haustorium, especially those of pharmaceutical and nutritional interests, then briefly discusses its commercial viability, shelf-life enhancement, culinary usage applications of haustoria, and concludes by some possible future focus that is quite promising to strengthen its status as a dietary component.

2. History of research and development of the Asian Palmyra Palm haustorium

The literature on *B. flabellifer* Linn and its scientific inquiry dates back to the 1960s specifically to seminal works such as the research by McCurrach's research in 1960^[1]. It is great in amount and literature from the 1900s primarily explored the distribution and development of the *B. flabellifer*^[2,11,12]. The focus on haustorium research in the 1900s was also aligned with its development, where the germination process was heavily investigated^[13–20].

2.1. The development of the haustorium

The augmented embryo which is transformed into a cotyledon structure in the period of seed germination is recognized as the haustorium^[13,16,19]. It is a distinct organ located at a point of the cotyledon that is away from the center. It withdraws nutrients from the endosperm to transfer them to the growing embryo, thereby leading to the enzymatic degradation of the endosperm as the haustorium and cotyledon develop^[13,15–17,19]. The endosperm cells are converted into a jelly-like, semi-solid mass that accumulates around the haustorium after degradation^[17]. This kind of germination is known as remote germination^[14,16], and it is noticeable in other kinds of palms as well^[21].

Cotyledons begin to grow and develop approximately six weeks after being nourished by haustoria. While the haustorium sustains the seed with lipids and insoluble polysaccharides, roots, and shoots appear from the proximal portion of the seed^[16,19,20,22,23]. Initially, carbohydrates tend to be metabolized faster than lipids, but when the seedling develops, the haustorium transforms triglycerides into carbohydrates, which are then quickly metabolized^[18,24]. After week twelve, a tuber emerges from the seed that gradually becomes the plant. After

approximately ninety days, the spongy haustorium, weighing about 25–30 g falls as the tuber begins to take in nutrients^[24].

2.2. Recent research and development on Asian Palmyra Palm haustorium

While discussions of *B. flabellifer*'s seed germination, and consequently, its haustorium development have made their way into 21st-century research^[22–24], with advancements in chemical analytic techniques and the growing realization of diverse uses of nearly every part of the *B. flabellifer* in the economy, society, nutrition, and medicine^[25–29], more attention has been attracted towards the phytochemical composition of various parts of the *B. flabellifer*, including the haustorium. As a result, recent research on the haustorium examines the molecules of the haustorium, their respective functions and uses, and their interactions with external factors^[24,30–34]. The findings of these studies will be discussed comprehensively in the following section. Regardless, it is worth mentioning that the most recent study on *B. flabellifer*'s haustorium was by Malayil et al.^[34], which looked into the potential of haustorium extracts to prevent pro-oxidant-mediated cell death and lipopolysaccharide (LPS) induced inflammation.

3. Phyto-chemistry of the haustorium

3.1. Nutritional value

Haustorium is white, spongy, and one of the edible goods of *B. flabellifer*^[35], granting it several nutritional, and subsequently, social, cultural, and economic benefits. More popularly, it is known as Thavan in Tamil Nadu, a sweet delicacy formed during the germination of the seed nut^[36–39]. During the period when the haustorium converts complex nutrients in the endosperm into simple forms for the growing embryo^[15,40], it is composed of varying essential sugars, amino acids, phytochemicals, bioactive compounds, and macro, and micronutrients, all of which are highly beneficial for human health^[24]. The nutritional value and physicochemical properties of the haustorium have been comprehensively studied by Wongsinchuan and Sirinupong^[30] and Vengaiah et al.^[33], illustrated in **Table 1**. Moreover, Vengaiah et al.^[33] also found that the spongy haustorium possessed glycosides, flavonoids, phenols, and saponins.

Table 1. Physicochemical properties and nutritive values of flour made from *B. flabellifer* Linn's haustorium^[30,33,41].

Parameter/nutrient	Mean values/100 g
pH	7.00
Total soluble solids (%Brix)	6.00
Moisture (%)	5.50–6.25
Ash (%)	5.00–5.15
Protein (%)	5.40–7.22
Fat (%)	0.31–2.10
Total carbohydrates (%)	70.00–76.05
Fiber (%)	5.03
Calcium (mg/100 g)	24.73–265.00
Sodium (mg/100 g)	171.43
Magnesium (mg/100 g)	164.22
Potassium (mg/100 g)	1833.19
Iron (mg/100 g)	4–4.24
Zinc (mg/100 g)	0.63
Phosphorus (mg/100 g)	290
Ascorbic acid (g/100 g)	1.63 ± 0.33
Energy (Kcal 100 g ⁻¹)	320.5 k.cal

One important aspect to note is that the amount of dietary fiber in the haustorium appears to be relatively higher after the twelfth week, particularly because fiber is difficult to break down^[24]. In addition, a longer incubation period may also lower the total phenolic content and the antioxidant activity of haustorium^[31]. Regardless, at the end of the twelfth week, the haustorium exhibits an appreciable amount of nutritive value,

including protein content, phenolic content, and even sugar, which reaches the optimum value during this time^[24]. However, after this time, the amount of sugar decreases, attributed to the degradation. On the other hand, Wongsinchuan and Sirinupong^[30] found that the fresh weight increased with the increasing incubation period, with four months of incubation period being when the weight of the haustorium was the highest. Later, the haustorium, along with the endosperm, slowly contributes to the formation of the tuber (another edible portion of the plant), which is heavily saturated in starch content^[25,42–44].

A summary of the nutritional changes in Palmyra Palm Haustorium during its growth stages, as discussed above, has been provided in **Table 2**.

Table 2. Nutritional changes in Palmyra Palm Haustorium during growth stages^[24,25,30,42–44].

Growth stage	Nutrient	Changes observed
After 12 weeks	Dietary fiber	Higher dietary fiber content, difficult to break down
After 12 weeks	Phenolic content	Lower phenolic content, reduced antioxidant activity
End of 12 weeks	Protein content	An appreciable increase in protein content
End of 12 weeks	Sugar content	Sugar content reaches the optimum value
After 12 weeks	Sugar content	Sugar content decreases due to degradation
Increasing incubation period	Fresh weight	Fresh weight increases with a longer incubation period
After 4 months	Starch content	Formation of tuber with high starch content

3.2. Molecular composition and medicinal properties

The presence of iron, potassium, phosphorus, calcium, sodium, carbohydrates, protein, fiber, phenolic compounds (gallic acid and chlorogenic acid), clindamycin, ascorbic acid, and fatty acids (hexadecanoic acid and myristic acid) makes Palmyrah Haustourium a very good nutraceutical material that can help fight against malnutrition issues among vulnerable rural populations^[45]. Flabelliberins are the spirostane-type steroidal saponin compounds available in Palmyrah sap, fruits, and tubers, so there may be a possibility for the presence of a trace amount of flabelliferins in haustorium^[29].

The haustorium and its extracts offer various medicinal properties, thanks to the presence of various chemicals, such as glycosides, flavonoids, phenols, saponins, and bioactive polyphenols. For example, the presence of glycosides allows the haustorium extracts to reduce hypertension^[33,46]. Additionally, flavonoids serve as anti-allergic, anticancer, and anti-neoplastic agents for various chronic diseases and disorders^[33]. Similarly, bioactive polyphenols fight oxidative stress that causes health issues like cancer, aging, and cardiovascular diseases^[33,47]. In addition, saponin, a bioactive antibacterial agent in many plants, can help tackle hypercholesterolemia, hyperglycemia, and obesity^[33]. Perhaps one of the most important pieces of research conducted on *B. flabellifer*'s haustorium is the recent study on it. Malayil et al.^[34] found that *B. flabellifer*'s haustorium extracts prevent pro-oxidant mediated cell death and LPS-induced inflammation. This means they can serve as efficient antioxidants and anti-inflammatory agents.

Despite its many medicinal properties, the medicinal use of the haustoria and the other parts of the *B. flabellifer* was absent from the Hortus Malabaricum, the oldest comprehensive printed book on the natural plant wealth of Asia and the tropics published from Amsterdam during 1678–1693^[48].

A summary of its molecules/nutrients, medicinal properties, compounds, effects, and applications discussed above have been provided in **Table 3**.

Table 3. Nutritional value and medicinal properties of *B. flabellifer* Linn's haustorium.

Molecules and nutrients	Medicinal Property	Compound	Effect	Applications
Moisture, ash, protein, fat, fiber, carbohydrate, iron, calcium, sodium, magnesium, potassium, phosphorous, iron, zinc, phosphorous, flavonoids, saponins, Clindamycin, Sucrose, Hexadecanoic acid, Myristic acid, phenols, Gallic acid, chlorogenic acid	Hypertension Reduction	Glycosides	Reduces hypertension	- flour market capacity - to be marketed as a delicacy internationally by increasing shelf-life
	Anti-allergic	Flavonoids	Acts as an anti-allergic agent	
	Anticancer and anti-neoplastic	Flavonoids	Exhibits anticancer and anti-neoplastic properties	
	Antioxidant	Bioactive polyphenols	Fights oxidative stress	
	Antibacterial	Saponin	Acts as a bioactive antibacterial agent	
	Anti-inflammatory	Haustorium extracts	Prevents pro-oxidant-mediated cell death and LPS-induced inflammation	

4. Commercial viability, shelf-life enhancement, and culinary usage

As mentioned above, haustorium can be exploited for commercial purposes by processing it as flour^[33]. This flour, as discussed, has wide-ranging nutritional and medicinal values attributed to its phytochemical composition^[33,49]. The functional properties of the flour include high water and fat/oil absorption capacity, which can enhance the food-eating quality^[33], thus making haustorium-based flour competitive in the market.

As a famous delicacy, *B. flabellifer*'s haustoria has been identified as one of the minor fruits that can be used to generate rural employment^[38]. In addition, though haustorium is a seasonal product, it can be marketed for a longer period by increasing its shelf-life, especially for the international market, as proposed by Tharmaratnam et al.^[32]. Haustorium's shelf life can be increased by 120 days if a preservative of sucrose media at the isotonic level at a pasteurized temperature of 90 °C with 15 °Brix medium is used^[32]. Palmyra haustorium powder was found to be superior in all nutritional aspects compared to Palmyra haustorium milk and Palmyra haustorium milk extracted cake powder^[45].

The versatility of the haustorium from the Asian Palmyra Palm extends beyond science and agriculture and leads to a treasured part of cultural heritage. For generations and centuries, many communities in regions where this palm thrives have harnessed the haustorium's unique properties to shape their traditions. The haustorium has stood out as a source of inspiration and sustenance for many communities where its sap is transformed into sweet delicacies^[37,50]. The waste seed cover can be used for cooking and to make activated charcoal and carbon nanomaterials, and it can be used in various applications.

Moreover, the sale of haustorium, as shown in **Figure 2**, as street food has become a cherished tradition in South Tamil Nadu, deeply rooted in the region's rich cultural tapestry. This delicacy has gained popularity as a seasonal treat that locals eagerly anticipate. In rural areas, the usage of haustorium in this traditional way makes it quite popular. The consumption of haustorium during in-demand seasons is not just a culinary experience but a cultural celebration of culinary heritage.



Figure 2. Haustorium is sold as a traditional delicacy in Mathalamparai, Tenkasi, South Tamil Nadu.

5. Future directions and recommendations

In the field of Palmyra palm haustorium research, uncharted molecules should be explored, with a new focus on identifying fresh compounds within the haustorium. This initiative for the new compounds should be driven by curiosity to utilize its maximum potential, as it could contain transformative pharmaceutical, nutritional applications, and ethnobotanical significance.

The pharmacological field should be prioritized, and researchers could dig more into the medicinal properties of haustorium compounds. In doing so, their therapeutic potential prompted with in-depth inquiries, has the potential to set intricate mechanisms in action. Clinical trials, dosage optimization studies, etc. could be conducted to validate their effectiveness in treating various medical conditions. This approach holds the promise of introducing novel pharmaceutical interventions with far-reaching implications for human health. The nutritional studies should focus more on refining cultivation techniques to ensure that the haustorium's nutritional content is maximized, and hence, its status as a sustainable and beneficial dietary component is strengthened. Researchers should also focus on the bioavailability of nutrients and their impact on human health, to establish the haustorium as a dependable and reliable source of essential nutrients. Moreover, information on the Palmyra palm haustorium's ethnobotanical significance is limited. Therefore, it is essential to explore such values; because in doing so, not only the biological wonders but also various cultural treasures deeply rooted in the heritage of the communities can be highlighted, which have relied on the Palmyra palm for generations.

6. Conclusions

The palmyra haustorium has several nutritional and medicinal values, as a result of the presence of many important organic compounds, nutraceuticals, and micro and macronutrients, and they are known for improving human health and well-being. Palmyra haustorium can be exploited for commercial purposes by processing it as flour and can be sold in the international market by increasing its shelf-life, thereby generating rural employment. Despite its wide-ranging national and medicinal value, lots of haustoria are not consumed and left to waste within the shells. But sometimes consumption of haustorium in the germination stage may lead to an impact on the number of Palmyra plants. Rapid deforestation due to population growth and rising demand for fuel has been responsible for clearing a significant number of Palmyra trees. Thus, fruitful initiatives that involve knowledge dissemination among the people regarding its nutraceutical values through proper scientific approaches are important to draw interest toward its conservation initiatives.

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Conflict of interest

The authors declare no conflict of interest.

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