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Borneo's Indigenous Fruits as Natural Sources for Nano-Coating Applications: Nutritional and Antioxidant Insights

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ABSTRACT

Borneo's indigenous fruits represent an underutilized yet highly valuable resource with immense potential as natural antioxidants in food, health, and packaging applications. Rich in bioactive compounds such as flavonoids, polyphenols, anthocyanins, and carotenoids, these fruits exhibit strong antioxidant properties that support their use in functional foods, nutraceuticals, and food preservation. This review explores the nutritional composition, phytochemical richness, and antioxidant potential of selected Borneo indigenous fruits and their byproducts, while also highlighting their emerging relevance in nanoscience. Recent advances in nanotechnology have opened new avenues for enhancing the value and functionality of fruit-derived bioactives through nanoformulation techniques such as nanoemulsions and nanogels. These nanoscale systems improve the bioavailability, stability, and targeted delivery of antioxidants, making them more effective in health-related applications. Furthermore, the incorporation of these bioactives into biodegradable nano-coating films offers promising solutions for sustainable food packaging, wound healing, and cosmeceuticals. Despite their promising health benefits, research on the commercial applications of these fruits remains limited. Greater investment in scientific validation, commercialization, and conservation is essential to unlock their full potential. By bridging traditional knowledge with modern nanotechnology, Borneo's indigenous fruits can contribute significantly to climate-smart food systems, biodiversity preservation, and the circular bioeconomy.

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1. Introduction

Borneo's indigenous fruits, deeply rooted in the region's cultural and ecological heritage, represent a largely untapped reservoir of nutritional, medicinal, and economic potential. These fruits are rich in bioactive compounds such as polyphenols, flavonoids, anthocyanins, and carotenoids, which contribute to their strong antioxidant, anti-inflammatory, and cardioprotective properties. Despite their health-promoting potential, indigenous fruits remain underutilized in modern food systems due to limited commercialization, low consumer awareness, and socio-economic biases [1,2]. Historically, indigenous fruits have been undervalued due to social and economic biases, often perceived as subsistence foods for marginalized communities or as fodder for animals. However, these fruits hold immense cultural, medicinal, and nutritional significance for local populations. In many indigenous cultures, these fruits are deeply embedded in traditional knowledge systems, symbolizing health, medicine, and even religious beliefs [3,4]. Traditional and indigenous food systems have long provided essential nutrients to local populations, with indigenous fruits playing a crucial role in human nutrition and dietary diversity. The increasing shift towards processed and convenience foods has further marginalized indigenous fruit consumption, despite their potential as functional food ingredients [5].

Malaysia, particularly the Borneo region, is home to over 370 fruit species, with approximately 95% classified as indigenous or rare [6]. Fruits such as bambangan (*Mangifera pajang*), dabai (*Canarium odontophyllum*), matoa (*Pometia pinnata*), and engkala (*Litsea garciae*) are notable for their high antioxidant content [7,8]. Research has demonstrated that many of these indigenous fruits possess significant nutritional and functional properties, being rich sources of dietary fiber, vitamins, minerals, as well as bioactive compounds with antioxidant potential [9]. These fruits can be consumed fresh, processed into value-added products like juices, jams, as well as fermented beverages, or utilized for medicinal and therapeutic purposes [10]. Despite their nutritional value, the consumption and commercialization of indigenous fruits stay limited caused by low consumer awareness and market demand. However, the increasing shift toward processed foods and the marginalization of traditional food systems have led to a decline in their cultivation and consumption, threatening both biodiversity and cultural heritage.

In recent years, the convergence of food science and nanotechnology has introduced new opportunities to enhance the functional value of these underutilized fruits. Nanoscience enables the development of nano-formulations such as nano-emulsions and nanogels that improve the bioavailability, stability, and targeted delivery of fruit-derived phytochemicals. These innovations not only amplify the health benefits of indigenous fruits but also support their application in sustainable food packaging, wound healing, and cosmeceuticals through nano-coating technologies. This review explores the nutritional composition, phytochemical richness, and antioxidant potential of selected Borneo indigenous fruits, while highlighting their emerging relevance in nanoscience. By bridging traditional knowledge with modern innovation, this work aims to promote the sustainable utilization, scientific validation, and global recognition of Borneo's indigenous fruits as valuable bioresources for health, industry, and environmental sustainability.

2. Distribution, description, and ecology of specific indigenous fruits in Sarawak

2.1 Bambangan

As for Bambangan (*Mangifera pajang*), the tree can grow approximately 30 meters tall and has quite a distinct cylindrical bole of trunk with diameter of 30 to 70 centimetres with either broadly or smooth fissured grey tree bark [11]. For the leaves, when the leaves are matured, they are elliptic

oblong in shape as well as dark green in colour but for the young leaves, they are usually bronze to pink in colour. As for the flowers, it consists of five petals with purplish red in colour on the inside and pinkish white on the outer side. The fruit of *Mangifera pajang* is usually oval and weighs around 0.5 to 1.0 kg. The fruit's skin is brown in colour and has rough texture. On the other hand, for the pulp, it is quite aromatic, very juicy once ripe, bright yellow in colour, highly fibrous and has that sweet-sour taste, quite similar to other *Mangifera* species [12,13]. *Bambangan* can commonly be found in the fully shaded lowlands of Borneo rainforests, majorly in Sabah [8].

2.2 Asam Kendong

Asam kendong (*Garcinia forbesii*) is a plant that grows well in a tropical environment that is known to be humid. It can be commonly found growing in primary and secondary forest including pear swamp forest [14,15]. *Garcinia forbesii* is an evergreen tree. It may grow up to a small to a medium size which is an average 5 to 33 m high adhered with a bole about 23 cm [16]. The tree bark is rough, and the branches are often black containing yellow latex. The leaves decorating the branches of this tree are simple and opposite. The colour of these leaves is dark green above while it is paler green below. The leaves are usually 3.5 cm to 17 cm long having a 2 cm to 7 cm width. Like any other fruiting tree, *Garcinia forbesii* tree produces flowers. The flowers are pale yellow in colour. The sepals are orange while the petals are pale yellow to light pink colour. The fruit of asam kendong is cherry-like and has a colour that changes from yellow to red when ripened. The fruit is described as having a taste similar to mangosteen which is juicy, sweet and sour [17].

2.3 Dabai

The trees within the Dabai (*Canarium odontophyllum*) genus grow to heights of 40–50 m (130–160 ft) as medium to large, buttressed trees. Each leaf type of Dabai belongs to alternate, pinnate, spiral, and stipulated categories and displays oblique, entire, dentate, or serrate folioles that frequently develop thickened tips. The direction of secondary nerves is longitudinal, and tertiary nerves show reticulating patterns. The flowers grow as a panicle type which emerges from leaf axils. The outer bark exhibits either a greenish-gray or light yellow-brown hue with smooth or scaly or lenticel-dotted appearance. The outer bark remains thin and underneath it lies rosy brown or reddish-gray laminated bark that is smooth with moisture and oozes a sticky or oily resin [18–20]. The mature fruits appear as plums with drupe features which consistently turn blue-black when they reach their ripeness. *Canarium* species thrive in primary and secondary rainforests, particularly in moist soils with full sunlight absorption. They require moderate water intake and are native to Borneo, including Sabah, Sarawak, Brunei, Kalimantan, Sumatra as well as Palawan Island. Propagation methods include patch budding, grafting, tissue culture, and vegetative propagation [21,22]. These trees thrive in high rainfall areas where annual precipitation should stay between 2,000–3,000 mm yet they can withstand up to 6,000 mm. They need organically sandy loam soils that are deep, moist and rich and crumbly for optimal growth and can tolerate pH levels from 4.5–6.5 up to 7.4. Both well-drained and poorly drained woodlands serve as suitable environments for *Canarium* species to survive [7].

2.4 Matoa

Matoa fruit (*Pometia pinnata*), which has a taste like longans, rambutans, and lychees and is also good for the body's health and beauty. Matoa originates as a tropical fruit primarily from Malaysia,

Sri Lanka, Philippines, Papua, the Pacific Islands and East Indonesia [23,24]. The fruit remains scarce in other regions of the world. The fruit exceeds the size of longan and features a rigid external covering. The immature Matoa develops green coloration which transforms into purplish red and green colors as well as dull brown and almost black shades based on its different varieties. The yellowish white pulp contains thick sweet sections that produce a chewy texture. Its single seed appears as a kind of nut. The edible seed of the fruit can be prepared through roasting or boiling methods [25,26].

2.5 Engkala

Litsea garciae, which is identified as Engkala by Borneo community. The fruits are 2.0 to 3.5 cm diameter wide with texture like dabai but possess a larger seed. Its flesh can be seen to be pale green-yellow and light pink once ripe. The tree is evergreen and can bear fruits annually [27]. It also has a sub-canopy characteristic and broadleaved. This fruit grows well with moist soil and abundance in the riparian and secondary forest of Borneo [28]. The propagation method that is suitable for the growth of engkala is by stem cutting or seed. The seeds can be sowed after the last frost and germination of seedling can be done with the usage of damp tissues instead of direct sowing into soil for germination. Before eating, cover the fruit with hot water and let it sit for a few minutes to soften.

2.6 Tarap

In Sarawak, Malaysia, tarap is common in secondary forests up to 1,000 meters altitude on sandy clay soils. The species thrives in partially shaded areas at elevations ranging from sea level up to 800 meters. It is known botanically as *Artocarpus odoratissimus* and is the Moraceae plant family member [29]. The fruit can be seen as a hybrid between the jackfruit and breadfruit from the perspective of morphology. Despite being such a potential food source, their flesh and seed are not fully utilised [30]. Tarap trees can grow up to 25 meters tall. The leaves are broad, ranging from elliptic to obovate in shape, measuring 15–50 cm long and 8–28 cm wide. They have a glossy green upper surface and a velvety-textured underside. The fruit is round to oblong, approximately 16 cm length and 13 cm diameter, having a green-yellow rind covered in soft, short spines. The flesh is white, juicy, and fragrant, enclosing ellipsoid seeds about 12 mm long.

2.7 Buah ucung

Baccaurea angulata, commonly known as buah ucung among the Iban ethnic group in Sarawak, is an indigenous fruit species native to Borneo. It is also found in certain regions of Indonesia [31]. This perennial tree is classified under the Euphorbiaceae family and naturally thrives in the tropical primary and secondary riverine forests of Borneo. The tree grows between 6 to 21 meters tall and features elliptic to obovate leaves. Its fruits develop in dense clusters and are distinctively glossy, pinkish-red, and angular with an obovoid star-shaped structure. The fruit's thick pericarp encases a white arillode, which is known for its mildly sweet and tangy taste [32].

Beyond its cultural significance, buah ucung is valued for its nutritional as well as medicinal characteristics. It is rich in antioxidants, particularly anthocyanins, which contribute to its vibrant coloration and possible health advantages. Studies have also highlighted its potential as a natural source of bioactive compounds having anti-inflammatory and antimicrobial characteristics properties [33,34]. Due to its preference for humid environments, *B. angulata* flourishes in moist, well-drained soils having high organic content. The species is typically found along riverbanks and lowland forests,

where it benefits from high rainfall and partial to full sunlight exposure. While traditionally propagated through seeds, vegetative propagation techniques like grafting as well as tissue culture are being explored to enhance cultivation and conservation efforts.

2.8 Buah Engkabang

Shorea macrophylla is also known as Engkabang, Kawang and Tengawang, is a member of the Dipterocarpaceae family and is grouped under the genus *Shorea*. It is found in Southeast Asian tropical rainforests. It favours damp environments like riverbanks and alluvium that is occasionally wet [35]. *Shorea macrophylla* is a stocky tree that can reach a height of 45 metres and has a dense, rectangular to hemispherical crown. Fruit petals at anthesis are firmly imbricate, cupped to form a vase-like chamber, and twisted at the base. The *Shorea macrophylla* has brown nuts measuring 13 to 21 millimetres long and 8 to 12 millimetres broad that make up the fruit which are widely utilized as a replacement for cocoa butter fat and are a favoured food source for wildlife [36].

Table 1

Contemporary applications of indigenous fruits and their derivatives.

Indigenous Fruit	Applications of Indigenous Fruits and Their Byproducts	Therapeutic Applications of Indigenous Fruit	Therapeutic Benefits of Various Plant Parts	References
Bambangan (Mangifera pajang) 	Eaten fresh, pickled, processed into jams and sauces	Rich in antioxidants, supports digestive health, anti-inflammatory properties	Leaves used for wound healing, bark used in traditional medicine	[37]
Asam Kendong (Garcinia forbesii) 	Consumed fresh, made into juice, vinegar production	Used to treat digestive issues, anti-microbial properties	Bark used for anti-inflammatory treatments, leaves used for herbal remedies	[38]
Dabai (Canarium odontophyllum) 	Eaten fresh, fermented, used in cooking	Lowers cholesterol, promotes heart health	Leaves used for traditional poultices, bark has antimicrobial properties	[7,39]
Matoa (Pometia pinnata)	Consumed fresh, dried, used in confectionery	Rich in vitamin C, boosts immunity, anti-inflammatory	Roots used in herbal medicine, bark used for anti-	[40]



Engkala (*Litsea garciae*)



Tarap (*Artocarpus odoratissimus*)



Buah Ucing (*Baccaurea angulata*)



Engkabang (*Shorea macrophylla*)



inflammatory
treatments

Eaten fresh, used in traditional desserts	Antioxidant-rich, supports cardiovascular health	Leaves used for reducing fevers, bark used in traditional medicine	[10]
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Eaten fresh, made into chips, desserts	Rich in fiber, aids digestion, boosts immune system	Roots used in traditional medicine for digestive health	[41]
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Eaten fresh, processed into syrup and jams	High in anthocyanins, promotes heart health	Leaves used in poultices for skin ailments	[42]
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Used for oil extraction, added to food products	Moisturizes skin, used in traditional wound healing	Bark and leaves used for treating skin conditions	[35,36]
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3. Current uses of selected indigenous fruits

3.1 Bambang

Local people majorly use bambangan fruit in culinary. For its flesh, it is usually eaten fresh just like any other mango species. Even though people consider this fruit waste useless the aromatic fragrance of its peel enables cooking various traditional dishes [43]. People commonly use the thick mango peels to enhance curry dishes because they eventually produce mango-like scents and flavors. The peel can also be pickled after de-skinning and cut into small pieces which later be mixed with some salt or sugar then, being left fermented for at least a year which be known as 'Jeruk Bambang'. Some may also add 'bird eye chili' to make it spicy [8]. Bambang is highly cultivated in Sabah by the Kadazan-Dusun community because the fruit played a major role their traditional cuisine called 'Hinava', a salad-like dish which often be mixed with few pieces of fresh raw fish, lemon or lime juice along with chili, ginger and onion. In Sarawak, the young leaves of bambangan are sold in the markets, commonly consumed as fresh salad (ulam) (Tangah et al., 2017). Commercial wise, *Mangifera pajang* pulp and juice powders are usually utilized as additional ingredients in several food products [13].

3.2 Asam Kendong

Asam kendong is commonly consumed raw by local communities, though some prefer eating its skin with sambal. The fruit is also dried and used as a flavoring ingredient in various dishes, while its skin is dried, fried, and incorporated into meals for added texture [16,44]. The young shoots of asam kendong are traditionally prepared as vegetables, often cooked together with asam ara. Additionally, the wood of asam kendong is valued for its resin and is dried and processed for furniture production. The primary use of this plant lies in its edible, sour-sweet white fruit, with its rind serving as a natural flavor enhancer in culinary applications [38]. In traditional medicine, *Garcinia forbesii* King has been used in East Indonesia to treat diabetes and malaria. Research indicates that *G. forbesii* King may contain bioactive compounds with potential pharmacological applications [45]. The fruit's outer layer is also utilized as both an herb and a spice, contributing a distinct sour flavor to various dishes.

3.3 Dabai

Research demonstrates without doubt that dabai fruit provides essential nutrition while also having medicinal value. The nutritional value of Dabai fruit includes protein and fat alongside energy content and carbohydrates. The low iodine content of dabai leads to high quality and extended shelf stability because it reduces oxidative spoilage. The hydrogenation process of dabai oils benefits from its high saponification value which enables its use as a substitute for traditional oils in soap production as well as shampoos. The product contains ample amounts of both phenolic compounds and vitamin E including γ -tocopherol [22,46]. Research shows dabai extract possesses the ability to decrease cholesterol levels present in plasma. The consumption of dabai extract helps lower LDL levels while increasing HDL levels in the body. LDL cholesterol levels are responsible for a variety of diseases, while atherosclerosis refers to a malignant disease condition caused by the plaque buildup in the arteries. Prolonged illness may eventually result in stroke and heart attack [20].

3.4 Engkala

Engkala (*Litsea garciae*), is a small fruit that commonly can be consumed raw or cooked, typically served as a Sarawakian side dish with salt. It is because this fruit has a creamy taste, and has a similar flavour to avocado. Other than that, it may be utilized for medicinal remedies. According to Kitoi et al. [27], Bidayuh and Iban populations apply it as an antidote for snake, centipede, and scorpion bites. Besides, the leaves of engkala are applied to treat skin burn, skin diseases and palm infections [45]. It is also used for curing skin conditions, blood in the stools, sprained ankles and knees, and muscle pain. In addition, the seed oil extracted from *L. garciae* serves as a raw material for both candle and soap manufacturing [28].

3.5 Matoa

For matoa fruit, despite being a small fruit, matoa fruit has many advantages. Matoa may serve as an immunity booster. The high vitamin C content of matoa is excellent for boosting your immune system. To combat common diseases, it will be stronger and healthier. You won't ever experience common illnesses again, if at all. Then, if a person had great immunity, they could still survive if they had viral protection. Antioxidants and vitamin C can be consumed to strengthen their immune system. The matoa fruit has both. Fruits from the matoa plant have high levels of vitamin C and powerful antioxidants that assist them fight viral defence. Vitamin C and vitamin E are both present in matoa fruit [23]. These two vitamins combined will provide the body with an excellent amount of antioxidants. The matoa fruit can boost fertility. Consuming matoa fruit can boost fertility and the likelihood of becoming pregnant. It is stated for both men and women as well. It may improve sperm quality. If they regularly consume matoa fruit, both men and women can have higher fertility. Cancer, the most hazardous disease in the world, can also be avoided by eating matoa fruit. This fruit has a high level of antioxidants and vitamin C, both of which are beneficial for preventing cancer. Antioxidants can counteract free radicals and stop the growth of cancer [40]. Lastly, matoa fruit shows anti-obesity properties which can benefit body tissues due to compounds in the matoa peel that block intestinal fatty acid absorption.

3.6 Tarap

Furthermore, tarap is usually for eating and medicinal purposes. It can be eaten raw. Tang et al. [29] investigated the young fruits of tarap usually used as sauce and stewed with meat or cooked with spices and coconut milk. Also, when roasted or cooked, the seeds become edible. The meat may be fermented to make organic vinegar, used to taste like ice cream, or usually combined with flour as well as egg batter and cooked as tarap fritters. Additionally, Nyokat et al. [47] mentioned the medicinal benefits of tarap for treating inflammation alongside malarial fever, diarrhoea as well as diabetes and tapeworm infection. The Sarawak population uses tarap fruit to treat both centipede and scorpion stings by sprinkling leaf ash onto the wounds and blends the ash with coconut oil to treat scabies.

3.7 Buah ucung

Buah ucung or Belimbing Hutan and Belimbing Darah in Malay is a flowering plant species and Tampoi family fruit tree native to Southeast Asia [48]. The uses of Ucung (*Baccaurea angulata*) are diverse, ranging from traditional culinary applications to emerging therapeutic and nutritional uses.

Traditionally, the fruit is consumed locally in Borneo as a fresh fruit or incorporated into various dishes such as fruit juice due to its unique sour taste and nutritional value, including their fruit peel which can be utilized to produce a fruit jam [33]. Previous studies have highlighted the fruit's rich content of antioxidants, particularly flavonoids and phenolic compounds, which have inspired exploration of its potential role as a natural ingredient in functional foods and dietary supplements aimed at combating oxidative stress and related health conditions [34].

3.8 Buah Engkabang

Buah Engkabang has a variety of traditional and modern applications, primarily in Southeast Asia, especially in Sarawak, Malaysia, and Indonesia. Traditionally, indigenous communities have utilized highly valued seeds which are processed into Engkabang butter, sometimes called "Borneo tallow" [49]. This butter has been traditionally utilized by indigenous communities for cooking, as a food additive, as an ingredient in animal feed and even for making soap and candles and biofuel due to its high oil content and beneficial properties [35,50]. Additionally, the oil extracted from *Shorea macrophylla* seeds has medicinal applications particularly in treating skin conditions. It is also utilized in cosmetic formulations, given its emollient properties and similarity to shea butter [51]. Traditional medical applications of this plant species include treating diarrhea and toothaches, skin diseases, ear problems as well as wounds while the plant extracts and secondary metabolite compounds demonstrate robust antioxidant, antimicrobial, anticancer, anti-diabetic, anti-obesity, antiulcer activity and protect the liver and. Modern research explores Engkabang oil as a natural personal care ingredient because it provides moisturization and anti-inflammatory properties which enhance skin hydration and improve the hydration benefits of tallow [36].

4. Phytochemical content and composition of the selected Indigenous fruits

4.1 Bambang

Wong and Siew [52] isolated 50 volatile constituents from the pulp of fully ripe fruits using vacuum distillation, followed by extracting the distillates with dichloromethane. The researchers utilized both Supelcowax-10 as well as SPB-1 columns in gas chromatography (GC) to analyze the volatile components of Bambang fruit. The Kovats index was utilized to facilitate compound identification based on retention times, enabling accurate characterization of the constituents. The analysis identified five distinct chemical classes: monoterpene hydrocarbons, esters, terpenoids, non-terpenoid alcohols, and carbonyl compounds. Among these, monoterpene hydrocarbons constituted the largest proportion of the Flame Ionization Detector (FID) area are accounted for 91.3%, having α -pinene (67.2%) as well as α -phellandrene (11.0%) identified as the predominant components. The detailed percentages of the FID area for monoterpene hydrocarbons are presented in Table 2.

Khoo and Ismail [53] focused on isolating isoflavones, which are significant phytoestrogens found in plants. Their study aimed to extract daidzein (Dn) and genistein (Gn) from the flesh of Bambang. They optimized the extraction process by heating the fruit at 80°C for 90 minutes. The optimal separation of isoflavones from Bambang fruits was attained utilizing a Zorbax Eclipse RP C18 column in high-performance liquid chromatography (HPLC) having a 1.00 mL/min flow rate. The average concentrations of Dn (8.49 ± 5.16 mg/100 g) and Gn (0.53 ± 0.74 mg/100 g) in the edible portion of Bambang fruit under optimized conditions are shown in Table 2. Additionally, Khoo & Ismail [53] conducted a comparative analysis with two other species of *Mangifera* fruits: *Mangifera foetida* (bacang) and *Mangifera odorata* (kuini). The study concluded that the Dn and Gn contents in

Bambangan were lower than those in kuini. However, Bambang exhibited relatively higher levels of Dn compared to bacang, while the Gn content was similar in both fruits.

The research team led by Abu Bakar et al. [37,54] conducted a comprehensive analysis of the phytochemical components in Bambang fruit. Their findings, as shown in Table 2, present various analyses to determine the total phenolic content (TPC), measured in milligrams of gallic acid equivalents per gram of dried sample (mg GAE/g); total flavonoid content (TFC), written in milligrams of rutin equivalents per gram of dried sample (mg RE/g); and total anthocyanin content (TAC), reported in milligrams of cyanidin-3-glucoside equivalents per 100 grams of dried sample (mg c-3-gE/100 g). Furthermore, the antioxidant properties were evaluated relying on the scavenging activity of 2,2-diphenyl-2-picrylhydrazyl (DPPH) radicals, quantified as milligrams of ascorbic acid equivalent antioxidant capacity per gram of sample (mg AEAC/g), and the ferric-reducing antioxidant power (FRAP) assays, expressed as the concentration of antioxidant with ferric-reducing ability per gram of sample ($\mu\text{M/g}$). These analyses were conducted using freeze-dried samples from the fruit's kernel, flesh as well as peel.

The findings from Abu Bakar et al. [37] revealed that the phenolic content in *M. pajang* followed the order of kernel, peel, flesh, having 103.30, 22.93 as well as 5.96 mg GAE/g values, accordingly. Significant differences ($p < 0.05$) were observed among the samples. In terms of flavonoid content, the kernel has the greatest concentration (10.98 mg RE/g), followed by the peel (7.50 mg RE/g) and the flesh (0.07 mg RE/g), with statistically significant differences ($p < 0.05$). Anthocyanins were present only in the flesh (1.47 mg c-3-gE/100 g) as well as the peel (28.29 mg c-3-gE/100 g). Regarding antioxidant activity, the kernel extract exhibited the strongest DPPH scavenging effect (23.23 mg AEAC/g), followed by the peel (20.32 mg AEAC/g) and the flesh (9.94 mg AEAC/g), all displaying significant differences ($p < 0.05$). Furthermore, the kernel demonstrated the greatest reducing capacity, approximately about 9 and 20 times greater than the peel and flesh, accordingly, with a FRAP value of $3130.00 \pm 35.47 \mu\text{M/g}$.

Bakar et al. [54] extended their investigation by analyzing and comparing the levels of selected polyphenols, which includes flavanones, phenolic acids, flavonols, and flavones, in *M. pajang*. They successfully isolated gallic, p-coumaric, sinapic, caffeic, ferulic, and chlorogenic acids (Table 2) from the kernel and peel of *M. pajang*. However, in the flesh sample, only chlorogenic, caffeic, as well as p-coumaric acids were present. A parallel trend emerged the flavanone content, where naringin and hesperidin were most abundant in the kernel, with concentrations of $294.50 \pm 98.20 \text{ mg/g dry weight}$ and $221.60 \pm 24.91 \text{ mg/g dry weight}$ ($p < 0.05$), accordingly, followed by the peel and flesh. In contrast, flavonol and flavone content displayed a different pattern. Quercetin, kaempferol, and rutin (flavonols), along with luteolin and diosmin (flavones), were most abundant in the peel, where all tested compounds were present, unlike in the kernel and flesh.

4.2 Asam Kendong

Asam kendong, a tropical fruit indigenous to Borneo, is recognized for its abundant phytochemical content and potential health benefits. Research has revealed substantial levels of phenolic compounds, flavonoids, anthocyanins, as well as carotenoids in its fruit, especially in the peel and flesh [16]. The occurrence of phenolic compounds and flavonoids plays a key role in the fruit's strong antioxidant capacity, which helps combat oxidative stress and reduce cellular damage. Anthocyanins, mainly found in the peel, are responsible for the fruit's reddish-purple coloration and have been linked to anti-inflammatory and neuroprotective properties. The high antioxidant activity of *G. parvifolia* suggests possible utilization in nutraceutical as well as pharmaceutical industries [44]. Research has also highlighted the fruit's acetylcholinesterase inhibition properties, indicating

possible benefits in cognitive health and neurodegenerative disease management. Additionally, its bioactive compounds exhibit antimicrobial and anti-inflammatory effects, making asam kendong a valuable candidate for functional food development [38].

4.3 Dabai

Prasad et al. [55] focused on isolating eight carotenoids (Table 2) from the pulp, peel as well as seed of *Canarium odontophyllum* Miq. in their study of the fruit's phytochemical composition. This focus was likely influenced by the distinctive coloration of the fruit, which often suggests the presence of carotenoids. Their findings indicated that all-trans- β -carotene was the predominant carotenoid, having concentrations of 69.5 ± 1.0 mg/kg in the peel, 31.1 ± 0.76 mg/kg in the pulp, and 15.1 ± 3.0 mg/kg in the seed. Besides all-trans- β -carotene, notable amounts of 15-cis- β -carotene, 9-cis- β -carotene, and 13-cis- β -carotene were also occurred in all three parts of the fruit. Pin et al., [56] extended this research by examining the variability of TPC and TFC in the skin, pulp, and kernel of six different dabai fruit genotypes: Biasa, Besar, Bujur, Jernah, Bulat as well as Seluang. Their study revealed that the skin extracts consistently indicated the greatest TPC and TFC values across all parameters, followed by the pulp and kernel extracts. Among the genotypes, the skin of Bulat exhibited the highest levels of TPC and TFC, with values of 26.62 ± 2.90 mg GAE/g dry weight and 46.70 ± 0.83 mg QE/g dry weight, respectively, as depicted in Table 2. These findings highlight notable variations in the phenolic as well as flavonoid content across different genotypes and tissue fractions of the dabai fruit.

4.1 Matoa

The phytochemical composition of the Matoa fruit (*Pometia pinnata*) from Sarawak, Malaysia, has not yet been investigated. Most studies, such as those conducted by Hanafi et al., [57], Irawan et al., [58] and Suzuki et al. [24] have focused on Matoa fruit samples from Indonesia. These studies identified key phytochemical components, including phenolic compounds, alkaloids, triterpenoids, and saponins. While these results give important observations into the phytochemical profile of the fruit, the absence of data on samples from Sarawak presents an opportunity for future research. Further studies on Sarawak-grown Matoa fruit could uncover new phytochemicals or variations in compound concentrations due to geographical and environmental factors, enhancing a deeper knowledge of the species.

4.5 Engkala

Research by Raduan et al. [59] focused exclusively on the bark extract of *L. garciae*. The phytochemical analysis of the bark extracts verified the existence of alkaloids, flavonoids, saponins, phenols, tannins, triterpenes, as well as steroids across four different solvent extracts: chloroform, hexane, methanol, and aqueous. These findings suggest an initial conclusion that the methanolic extract is especially abundant in phenolic compounds, notably flavonoids and tannins. Five years earlier, Wulandari et al. [60] carried out a similar study on the branch, bark, and leaf extracts of *L. garciae* from Samarinda, East Kalimantan. They also found that the greatest total phenolic as well as flavonoid contents were present in all plant parts, although they used ethanol as the extraction solvent. Building on this, Raduan et al. [59] further analyzed the methanolic bark extract using ultra-high-performance liquid chromatography-mass spectrometry (UHPLC-MS). Their assessment of

antioxidant capacity indicates that the methanolic bark extract, caused by its high phenolic and flavonoid content (Table 2), demonstrates potential as a valuable natural source of antioxidants.

4.6 Buah ucung

Ahmed et al. [34] conducted a study to extract phenolic compounds as well as other antioxidants from the pulp, skin, and whole fruit samples of *Baccaurea angulata*. The study compared the effects of two solvents, phosphate-buffered saline (PBS) and methanol, on the yield of TPC, TFC, total carotene content (TCC), free radical scavenging activities as well as lipid peroxidation inhibition activities. The findings showed that the pulp (edible portion) yielded the greatest content. Methanol extracts from all fruit parts exhibited significantly greater levels of TPC, TFC, and TCC in comparison to PBS extracts ($p < 0.01$). The research highlighted that *B. angulata* contains substantial amounts of primary antioxidants and demonstrates lipid peroxidation inhibition capacities comparable to those of blueberries, indicating its capability as a significant antioxidant source.

Hazali et al. [61] provided slightly different results in their investigation of the three fruit parts: pulp, skin as well as whole fruit of *B. angulata*. Their findings indicated that the pulp tested positive for tannins, while the skin showed a strong presence of flavonoids. In addition to phenolic content, Hazali et al. [61] also screened for other phytochemicals, including alkaloids, saponins, triterpenes, and steroids. However, all parts of the fruit tested negative for these compounds. Vitamin content analysis conducted revealed that vitamin A was present in the highest amount in the pulp, with none detected in the skin. Vitamin C was found throughout all parts of the fruit, with the greatest concentration in the pulp and the lowest in the skin. Interestingly, vitamin E was detected only in the skin and absent in the pulp and whole fruit.

4.7 Buah Engkabang

A comprehensive evaluation of the chemical composition of *Shorea macrophylla*, commonly known as Engkabang in the local Sarawak community, remains limited, particularly regarding the extraction and analysis of its chemical constituents. Most studies have predominantly focused on the commercially available *Shorea macrophylla* butter oil (SMBO), with researchers analyzing its phytochemical profile using samples purchased from local markets. In a recent study, Redhwan et al. [62] acquired Engkabang butter oil directly from the Iban community in Kanowit, Sarawak, and performed a comprehensive fatty acid analysis using the Association of Analytical Chemists (AOAC) 20th Edition method 996.06/GC-FID. The results revealed that saturated fatty acids were predominant, constituting more than 65% of the total fatty acid content, whereas unsaturated fatty acids made up around 35%. The major saturated fatty acids identified were stearic acid (around 45%), oleic acid (33%), and palmitic acid (16%). Further, Rao et al. [51] proposed that the high content of fatty acids in Engkabang butter oil suggests its potential as a valuable omega-6 lipid source, particularly for fish feed applications, highlighting its relevance in aquaculture nutrition.

Table 2

Phytochemical composition of Borneo indigenous fruits and their byproducts

Fruit/Fruit Origin	Fruit component	The solvent used	Identification method	Phytochemical compound detected	Concentration	Reference
Bambang an,	Pulp	Dichloromethane	GC	α -Pinene α -Phellandrene Limonene	67.15% FID area 11.01% FID area 4.60% FID area	[52]

Mangifera pajarang (Sabah)	Flesh	Ethanol	HPLC	Myrcene β-Phellandrene β-Pinene Daidzein (Dn) Genistein (Gn)	3.43% FID area 2.29% FID area 1.83% FID area 8.49±5.16 mg/100g 0.53±0.74 mg/100g	[53] [37]
Bambang an, Mangifera pajarang (Sarawak)	Flesh	Methanol	Spectrophotometer	TPC TFC TAC DPPH FRAP	5.96±0.34 mg GAE/g 0.07±0.00 mg RE/g 1.47±0.28 mg c-3-gE/100 g 9.94±0.22 mg	
Bambang an, Mangifera pajarang (Sabah)	Peel			TPC TFC TAC DPPH FRAP	AEAC/g 150.00±1.44 μM/g 22.93±0.36 mg GAE/g 7.50±0.09 mg RE/g	
	Kernel			TPC TFC TAC DPPH FRAP	28.3±0.70 mg c-3-gE/100 g 20.32±0.10 mg AEAC/g 343.17±7.25 μM/g	[54]
	Flesh	Ethanol [1:5 w/v]	HPLC	Gallic p-coumaric Sinapic Caffeic Ferulic Chlorogenic Naringin Hesperidin Quercetin Kaempferol Rutin Luteolin Diosmin	103.30±0.63 mg GAE/g 10.98±0.16 mg RE/g Not detected 23.23±0.03 mg AEAC/g 3130.00±35.47 μM/g Not detected 24.96±3.68 μg/g dw Not detected 26.75±0.55 μg/g dw Not detected	
	Peel			Gallic p-coumaric Sinapic Caffeic Ferulic Chlorogenic Naringin Hesperidin Quercetin Kaempferol Rutin Luteolin Diosmin	5.81±0.26 μg/g dw 1.45±0.27 μg/g dw 0.93±0.17 μg/g dw 165.10±6.08 μg/g dw 182.70±6.22 μg/g dw dw Not detected 292.10±7.27 μg/g dw dw Not detected 30.72±5.83 μg/g dw 199.00±17.53 μg/g	
	Kernel			Gallic p-coumaric Sinapic	dw 0.67±0.31 μg/g dw	

				Caffeic Ferulic Chlorogenic Naringin Hesperidin Quercetin Kaempferol Rutin Luteolin Diosmin	440.50±21.90 µg/g dw 784.20±144.10 µg/g dw 8.15±0.14 µg/g dw 1.51±0.23 µg/g dw 1.01±0.07 µg/g dw 81.85±21.17 µg/g dw 200.40±16.41 µg/g dw 132.10±19.21 µg/g dw 253.50±1.15 µg/g dw 198.50±2.56 µg/g dw 236.60±28.31 µg/g dw 301.10±19.12 µg/g dw 20.06±1.00 µg/g dw 150.00±13.48 µg/g dw 5334.00±513.90 µg/g dw 14.10±0.94 µg/g dw 294.50±98.20 µg/g dw 221.60±24.91 µg/g dw Not detected Not detected 721.10±34.13 µg/g dw Not detected 2386.00±325.10 µg/g dw	
Garcinia parvifolia	Peel Flesh	80% Methanol	Spectrophotometry	TPC TFC TAC TCC TPC TFC TCC	5.3 ± 0.1 mg GAE/g 3.7 ± 0.3 mg RE/g 4.4 ± 0.2 mg C3GE/100 g 17.0 ± 0.3 mg BC/100 g 7.2 ± 0.3 mg GAE/g 5.9 ± 0.1 mg RE/g 3.0 ± 0.0 mg BC/100	[45]
Dabai, Canarium odontop	Peel	Hexane/Acetone/Et	HPLC	all-trans-lutein 9-cis-lutein 13-cis-lutein	1.62±0.03 mg/kg 0.32±0.01 mg/kg 0.62±0.01 mg/kg	[55]

hyllum Miq (Kuching, Sarawak)	Pulp	hanol mixtur e [70:15: 15, v/v/v]		di-cis-β-carotene	0.69±0.01 mg/kg	
	Seed			15-cis-β-carotene	18.3±2.4 mg/kg	
9-cis-β-carotene		39.6±0.28 mg/kg				
all-trans-β-carotene		69.52±1.0 mg/kg				
13-cis-β-carotene		19.4±1.2 mg/kg				
all-trans-lutein		0.36±0.01 mg/kg				
9-cis-lutein		0.10±0.02 mg/kg				
13-cis-lutein		0.16±0.009 mg/kg				
di-cis-β-carotene		0.35±0.0005 mg/kg				
15-cis-β-carotene		11.9±0.3 mg/kg				
9-cis-β-carotene		5.8±0.69 mg/kg				
all-trans-β-carotene		31.1±0.76 mg/kg				
13-cis-β-carotene		5.7±0.5 mg/kg				
all-trans-lutein		0.67±0.01 mg/kg				
9-cis-lutein		0.13±0.04 mg/kg				
13-cis-lutein		0.11±0.01 mg/kg				
di-cis-β-carotene		0.37±0.01 mg/kg				
(Sibu & Kuching, Sarawak)	Skin	15-cis-β-carotene	8.38±0.4 mg/kg	[56]		
		9-cis-β-carotene	3.20±0.3 mg/kg			
		all-trans-β-carotene	15.1±3.0 mg/kg			
		13-cis-β-carotene	5.6±0.27 mg/kg			
		all-trans-lutein				
		9-cis-lutein				
		13-cis-lutein				
		di-cis-β-carotene	26.56 ± 0.32 mg			
	Pulp	15-cis-β-carotene	GAE/g			
		9-cis-β-carotene	24.74 ± 0.52 mg			
		all-trans-β-carotene	GAE/g			
		13-cis-β-carotene	18.33 ± 0.49 mg			
		TPC	GAE/g			
		Besar	26.60 ± 0.25 mg			
		Biasa	25.50 ± 0.40 mg			
		Jernah	GAE/g			
	Pulp	Bujur	26.62 ± 2.90 mg			
		Seluang	GAE/g			
		Bulat				
		TFC	24.17 ± 0.86 mg			
		Besar	QE/g			
		Biasa	37.19 ± 1.53 mg			
		Jernah	QE/g			
		Bujur	15.62 ± 0.22 mg			
	Kernel	Seluang	QE/g			
		Bulat	27.57 ± 0.63 mg			
		TPC	QE/g			
		Besar	28.01 ± 0.30 mg			
		Biasa	QE/g			
		Jernah	46.70 ± 0.83 mg			
		Bujur	QE/g			
		Seluang	3.62 ± 0.09 mg			
Bulat	GAE/g					

				TFC	2.46 ± 0.21 mg	
				Besar	GAE/g	
				Biasa	4.17 ± 0.34 mg	
				Jernah	GAE/g	
				Bujur	3.30 ± 0.06 mg	
				Seluang	GAE/g	
				Bulat	5.30 ± 0.37 mg	
				TPC	GAE/g	
				Besar	7.48 ± 0.26 mg	
				Biasa	GAE/g	
				Jernah		
				Bujur	12.79 ± 0.47 mg	
				Seluang	QE/g	
				Bulat	19.28 ± 0.74 mg	
				TFC	QE/g	
				Besar	20.68 ± 0.47 mg	
				Biasa	QE/g	
				Jernah	13.59 ± 0.66 mg	
				Bujur	QE/g	
				Seluang	19.17 ± 0.23 mg	
				Bulat	QE/g	
					24.55 ± 0.18 mg	
					QE/g	
					1.11 ± 0.14 mg	
					GAE/g	
					1.53 ± 0.09 mg	
					GAE/g	
					1.44 ± 0.03 mg	
					GAE/g	
					1.36 ± 0.06 mg	
					GAE/g	
					2.83 ± 0.22 mg	
					GAE/g	
					2.22 ± 0.29 mg	
					GAE/g	
					11.21 ± 0.23 mg	
					QE/g	
					12.12 ± 1.27 mg	
					QE/g	
					10.11 ± 0.18 mg	
					QE/g	
					11.66 ± 0.45 mg	
					QE/g	
					16.82 ± 0.71 mg	
					QE/g	
					19.31 ± 0.37 mg	
					QE/g	

Matoa, Pometia pinnata (Pontianak, West Kalimantan, Indonesia)	Flesh	Methanol	Phytochemical screening	Total phenolics	393.38 ± 0.28 mg GAE/g	[58]
Engkala, Litsea garciae (Sibu, Sarawak)	Bark	Methanol		TPC TFC DPPH FRAP	34.82±1.12 µg GAE/mg 16.18±2.13 µg QE/mg 0.130 ± 0.006 µg AAE/mg 280.010 ± 58.047 µg/mL	[59]
Buah Ucung, Baccaurea angulata (Bau, Sarawak)	Whole fruit	Methanol	UHPLC–MS	TPC TFC TCC	5229.64±71.89 µg GAE/g 28.23±0.84 mg QE/g	[34]
	Skin	PBS [1:10 v/v]	Phytochemical Screening Test	TPC TFC TCC	5229.64±71.89 µgBC/100g 4678.57±50.71 µg GAE/g	
				TPC TFC TCC	18.36±0.72 mg QE/g 545.65±19.91 µgBC/100g	
	Pulp			TPC TFC TCC	15357.77±150.72 µg GAE/g 37.32±0.55 mg QE/g	
				Whole fruit	TPC TFC TCC	
	Skin				TPC TFC TCC	
				Pulp	Alkaloid Flavonoid Tannin Saponin Triterpine and steroid	
	Whole fruit				Alkaloid Flavonoid Tannin Saponin Triterpine and steroid	
				Skin	Alkaloid Flavonoid Tannin Saponin Triterpine and steroid	
	Pulp				HPLC	

	Whole fruit Skin Pulp	Hexane		Triterpine and steroid β-carotene Ascorbic Acid Vitamin E β-carotene Ascorbic Acid Vitamin E β-carotene Ascorbic Acid Vitamin E	Negative test Negative test Negative test Weak positive test Negative test Negative test Negative test Positive test Negative test Negative test Negative test 0.00 ± 0.00 µg/100g 1.29 ± 0.00 mg/100g 7.79 ± 0.28 µg/100g 28.3± 12.45 µg/100g 2.57 ± 0.00 mg/100g 0.00 ± 0.00 µg/100g 25.2± 2.83 µg/100g 2.55 ± 0.00 mg/100g 0.00 ± 0.00 µg/100g	
Engkabang, Shorea macrophylla (Kanowit, Sarawak)	Engkabang butter oil or Shorea macrophylla butter oil (SMBO)	N/A	GC-FID	Saturated Fatty Acid -Stearic acid -Oleic acid -Palmitic acid Unsaturated Fatty Acid	65.2647% 45.8739% 33.5900% 16.8075% 34.7352%	[51]

GC: Gas Chromatography; HPLC: High-Performance Liquid Chromatography; GC-FID: Gas Chromatography Flame Ionization Detector; TPC: Total Phenolic Content; TFC: Total Flavonoid Content; TAC: Total Anthocyanin Content; DPPH: 2,2-Diphenyl-1-picrylhydrazyl (Free Radical Scavenging Assay); FRAP: Ferric Reducing Antioxidant Power; TCC: Total Carotenoid Content; PBS: Phosphate Buffered Saline; UHPLC–MS: Ultra-High Performance Liquid Chromatography–Mass Spectrometry; GAE: Gallic Acid Equivalent; RE: Rutin Equivalent; QE: Quercetin Equivalent; AEAC: Ascorbic Acid Equivalent; dw: Dry Weight; N/A: Not Available.

5. In vitro antioxidant activity of the selected indigenous fruits and their potential in nano-coating applications

Antioxidants are essential in preventing oxidative stress, which contributes to chronic diseases such as cardiovascular disorders, cancer, neurodegenerative conditions, and premature aging. The indigenous fruits of Borneo are rich in natural antioxidants, making them valuable not only for health and wellness applications but also for emerging technologies such as bioactive nano-coatings. These coatings can be used in food packaging, biomedical devices, and cosmetic formulations to provide antimicrobial protection, oxidative stability, and enhanced shelf life. The incorporation of fruit-derived antioxidants into nano-coatings offers a sustainable and functional approach to developing eco-friendly, bioactive surfaces. Each fruit exhibits unique antioxidant properties due to its distinct phytochemical composition, contributing to various health and material science benefits.

5.1 Bambang

Bambang stands out as a nutritional powerhouse, exceptionally rich in phenolics and carotenoids. The total phenolic content (TPC) of bambangan pulp is notably high, with the sweet-sour variety showing a remarkable 339.97 mg gallic acid equivalent (GAE) per 100 g of fresh edible portion [63]. As shown by Prasad et al. [64], a TPC of 12.9 mg GAE/g on a dry weight basis obtained with further optimised extraction condition. Beyond the pulp, the peel and kernel of the bambangan fruit are also rich sources of bioactive compounds. The peel has been identified as having a higher TPC and antioxidant capacity than the pulp. Phytochemical analysis has revealed a complex profile of phenolics including gallic acid, chlorogenic acid, vanillin, *p*-coumaric acid, and rutin [65]. The presence of these compounds, alongside significant levels of mangiferin, epicatechin, and catechin, underpins its potent antioxidant activity [64]. The high TPC and presence of potent antioxidants like mangiferin and rutin make bambangan a strong candidate for nano-coating formulations. These compounds can be encapsulated in nanocarriers to create coatings with enhanced oxidative resistance, suitable for biomedical implants or active food packaging. The stability and bioactivity of bambangan-derived antioxidants under nano-encapsulation conditions also support their use in controlled-release systems.

5.2 Dabai

Dabai is distinguished by its unique profile of bioactive compounds, including a significant presence of alpha-amyrin, beta-amyrin, and beta-sitosterol, which are known for their antioxidant and anti-inflammatory prowess. A comprehensive Gas Chromatography-Mass Spectrometry (GC-MS) analysis of the acetone extract from the stem bark has successfully identified 24 distinct phytochemicals. The major constituents, alpha-amyrin (16.66%), beta-amyrin (4.62%), beta-sitosterol (3.34%), and 9,12-octadecadienoic acid (3.20%), are the primary drivers of its health benefits. These bioactive compounds offer various health benefits, such as improving heart health by lowering cholesterol and reducing oxidative stress in blood vessels, which may lower the risk of cardiovascular diseases. Beta-sitosterol also supports brain function and may help prevent neurodegenerative diseases like Alzheimer's. Additionally, the flavonoids in dabai have anti-inflammatory effects, which may benefit individuals with arthritis and joint pain. The amyrins present in dabai have shown potential anti-cancer effects by inhibiting cancer cell growth and inducing apoptosis. In conclusion, the acetone extract of *Canarium odontophyllum* stem bark (dabai) contains bioactive compounds with medicinal properties, particularly alpha- and beta-amyrin, which may contribute to its cytotoxic effects on HCT 116 cells [66]. These bioactives can be integrated into nano-coatings to provide anti-inflammatory surfaces for wound dressings or antioxidant barriers in pharmaceutical packaging. The lipophilic nature of its compounds also supports their incorporation into lipid-based nanocarriers, enhancing coating adhesion and bioavailability.

5.3 Matoa

Matoa has significant antioxidant potential due to its high phenolic (197.21 mg GAE/g) and flavonoid (28.73 mg QE/g) content. The reflux extract of *Pometia pinnata* using ethanol as a solvent was tested for antioxidant activity using the DPPH method ($41.83 \pm 0.17 \mu\text{g/mL}$) and the ABTS method ($151.02 \pm 0.03 \mu\text{g/mL}$). The DPPH and ABTS assays confirm its strong radical-scavenging ability, which translates to various health benefits. Matoa's flavonoids help improve blood circulation and lower blood pressure, making it beneficial for cardiovascular health. Its rich Vitamin C content strengthens

the immune system and reduces inflammation, helping to combat infections. The polyphenols found in matoa safeguard against oxidative stress at the cellular level, lowering the risk of chronic diseases and mitigating aging-related damage [67,68]. With its high phenolic and flavonoid content, matoa is ideal for developing antioxidant-rich nano-coatings that can scavenge free radicals on contact surfaces. These coatings can be applied to cosmetic packaging or dermal patches, offering protection against environmental oxidative stress. The strong radical-scavenging ability of matoa extracts also supports their use in UV-protective coatings.

5.4 Engkala

The bark of the Engkala tree has demonstrated notable ferric reducing antioxidant power (FRAP), indicating its capacity to act as an effective electron donor in neutralizing oxidative stress. The methanol extract of Engkala has shown the most significant DPPH radical scavenging activity, with an IC₅₀ value of 280.01 µg/mL, highlighting its potential to shield cells from oxidative damage. This antioxidant activity is particularly beneficial for reducing inflammation, which makes engkala useful in managing chronic inflammatory conditions such as arthritis. Additionally, its hepatoprotective properties help shield liver cells from oxidative damage, making it a promising natural remedy for liver disorders. Furthermore, the antimicrobial effects of engkala's polyphenols and flavonoids suggest its potential for preventing infections and supporting overall health [10]. Its anti-inflammatory and hepatoprotective properties make it suitable for biomedical coatings that aim to reduce inflammation and oxidative damage. The extract's compatibility with polymer matrices enhances its application in biodegradable films.

5.5 Buah ucung

Buah ucung has demonstrated a significant capacity to inhibit lipid peroxidation and boost the activity of endogenous antioxidant enzymes, marking it as a key contributor to the body's defense against oxidative stress. It is particularly abundant in anthocyanins, the pigments responsible for its vibrant hue. These anthocyanins are instrumental in promoting cardiovascular health by helping to regulate cholesterol levels and prevent the buildup of arterial plaques, thereby reducing the risk of heart disease. Furthermore, the anti-inflammatory properties of buah ucung have been linked to improved insulin sensitivity, positioning it as a promising functional food for the management of diabetes. Research has also indicated that extracts from buah ucung may suppress markers of inflammation associated with obesity, highlighting its potential role in weight management and metabolic health. Studies on the ethanol extract of *P. angulata* have not only confirmed its antioxidant activity but also its ability to stimulate the proliferation of 3T3-L1 cells. Notably, the extract was found to suppress the migration of TGF-β-induced 3T3-L1 cells and downregulate the expression of HIF-1α and IL-6, suggesting complex cellular mechanisms underlying its beneficial effects [69]. The anthocyanin-rich profile of buah ucung provides both antioxidant and anti-inflammatory effects, making it suitable for color-stable, bioactive coatings. These can be used in functional food packaging to indicate spoilage or oxidative degradation. Its ability to regulate inflammation and metabolic markers also supports its use in therapeutic nano-coatings for metabolic health applications.

5.6 Engkabang

Engkabang extracts have been found to exhibit strong antioxidant activity, with DPPH IC₅₀ values of 1.025 mg/mL for the leaf extract and 0.693 mg/mL for the bark extract. This indicates its potency in neutralizing free radicals as well as protecting against oxidative damage. The antioxidant compounds in engkabang support skin health by aiding in tissue repair and wound healing, reducing oxidative stress on skin cells. Its neuroprotective properties are essential in safeguarding against cognitive decline and lowering the risk of neurodegenerative diseases. Furthermore, studies have demonstrated that *Shorea macrophylla* extracts enhance cellular resistance against oxidative stress, suggesting potential applications in anti-aging formulations and natural skincare products. For the assessment of antioxidant potential, the 2,2-diphenyl-1-picrylhydrazyl (DPPH) and ferric reducing antioxidant power (FRAP) assays were utilized. Pre-treatment with *S. macrophylla* extracts notably enhanced brine shrimp survival under H₂O₂-induced oxidative stress [36]. Engkabang's potent antioxidant activity and neuroprotective properties make it a promising candidate for anti-aging and neuroprotective nano-coatings. These can be applied in cosmeceutical products or smart textiles. Its ability to enhance cellular resistance to oxidative stress also supports its use in protective coatings for sensitive biomaterials.

6. The role of community, university, and government to unlock the potential of indigenous fruit

Unlocking the potential of Borneo's indigenous fruits requires collaboration between communities, universities, and governments. Each plays a key role in ensuring the sustainable use, economic benefits, and long-term preservation of these valuable resources. By working together, they can enhance food security, protect biodiversity, and create economic opportunities. Local communities are the backbone of indigenous fruit cultivation and conservation, relying on traditional knowledge passed down through generations. They preserve and cultivate native species like Bambangan, Dabai, Matoa, Engkala, and lesser-known fruits such as Ucing and Engkabang. Sustainable harvesting techniques and agroforestry practices help maintain biodiversity while improving food security. Community-driven cooperatives and small-scale enterprises add value to indigenous fruits, creating income opportunities and expanding market access. By integrating traditional knowledge with modern market strategies, communities can strengthen both conservation efforts and economic growth [70,71].

Universities contribute through research, documentation, and dissemination of knowledge about indigenous fruits, particularly their nutritional, medicinal, and commercial potential. Scientific studies highlight their health benefits, while extension programs educate farmers on sustainable farming techniques, pest control, and value addition. Collaborative projects between universities and farmers promote improved agricultural practices, productivity, and sustainability. Training programs further equip farmers with business and market skills, fostering economic expansion and broader market integration [72–74]. Governments support indigenous fruit industries by implementing policies that promote sustainable agriculture, conservation, and economic development. Policies encouraging agroforestry help preserve ecosystems while improving local livelihoods. Financial support, including grants, subsidies, and loans, assists farmers in acquiring better equipment, training, and market access. Infrastructure improvements, such as better roads and transportation networks, enhance supply chain efficiency, connecting rural farmers to domestic and international markets. Governments also facilitate trade agreements and export opportunities, ensuring sustainable sourcing and compliance with international standards [75–77]. By combining local knowledge,

scientific research, and government policies, indigenous fruits in Borneo can be sustainably managed and leveraged for economic and ecological benefits.

7. Conclusion

This review has underscored the remarkable nutritional, phytochemical, and antioxidant potential of Borneo's indigenous fruits, highlighting their value as underutilized yet powerful bioresources. Rich in phenolic compounds, flavonoids, anthocyanins, and carotenoids, these fruits offer significant health benefits, including anti-inflammatory, cardioprotective, neuroprotective, and anti-aging effects. Their integration into functional foods and nutraceuticals supports both human health and sustainable food systems. Importantly, the emerging application of nanotechnology presents a transformative opportunity to enhance the utility of these fruits. Nano-formulation techniques such as nano-emulsions, nanogels, and biodegradable nano-coating films—can significantly improve the stability, bioavailability, and targeted delivery of fruit-derived antioxidants. These innovations open new pathways for sustainable food packaging, wound healing, and cosmeceutical development. Despite their promise, commercial applications remain limited. Future research should prioritize value addition, safety validation, and scalable nano-coating technologies. Bridging traditional knowledge with modern innovation will be key to unlocking the full potential of Borneo's indigenous fruits for health, industry, and environmental sustainability. Expanding scientific exploration into the practical utilization of these underutilized bioresources is crucial for enhancing their market potential and sustainability. Strengthening research efforts on value addition and commercialization will be key to unlocking the full potential of these underutilized fruits, ensuring their sustainable utilization while supporting biodiversity conservation and local economies.

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References

- [1] Mudau FN, Chimonyo VGP, Modi AT, Mabhaudhi T. Neglected and underutilised crops: A systematic review of their potential as food and herbal medicinal crops in South Africa. *Front Pharmacol* (2022);12:1–31. <https://doi.org/10.3389/fphar.2021.809866>
- [2] Abu Bakar FI, Abu Bakar MF, Abdullah N, Endrini S, Rahmat A. A review of Malaysian medicinal plants with potential anti-inflammatory activity. *Adv Pharmacol Sci* (2018). <https://doi.org/10.1155/2018/8603602>
- [3] Rauf A, Ibrahim M, Muhammad N, Naz S, Wadood A, Khan B, et al. Enzyme inhibitory activities of extracts and carpachromene from the stem of ficus benghalensis. *Biomed Res Int* (2022). <https://doi.org/10.1155/2022/7053655>
- [4] Ibrahim NF, Zakaria NA, Aris F. Phytochemistry and biological activity of terung asam, indigenous fruit-vegetables of Sarawak - A review. *J Sustain Sci Manag* (2022)17:270–85. <https://doi.org/10.46754/jssm.2022.02.019>
- [5] Mukti, B. H. Ethnobotanical studies of medicinal plants in Borneo : Bridging tradition and pharmaceutical research. *Health Sciences International Journal* (2024). 2(2), 154–168.
- [6] Norzalila K, Nik Rozana NM, Nor Azlina S. Indigenous fruits consumption in Sabah and Sarawak. *Econ Technol Manag Rev* (2020);15:1–9.
- [7] Hamzah MH, Mohd Basri MS, Maringgal B, Mohd Ali M, Wondi MH, Che Man H, et al. Exploring Dabai (Canarium odontophyllum), indigenous fruit of borneo: A review of nutritional values, potential uses, emerging application in essential oil processing, and health benefits. *Plants* (2022);11. <https://doi.org/10.3390/plants11192646>
- [8] Mohd Fadzelly AB, Jeffrey RF. A review on underutilized indigenous bambangan (Mangifera pajang) fruit as a potential novel source for functional food and medicine. *J Med Plants Res* (2013);7:3292–7. <https://doi.org/10.5897/JMPR2013.5299>

- [9] Ismail HA, Ramaiya SD, Zakaria MH. Compositional characteristics and nutritional quality of indigenous fruit of *Artocarpus odoratissimus* Blanco. *Malaysian Appl Biol* (2023);52:187–203. <https://doi.org/10.55230/mabjournal.v52i5.icfic15>
- [10] John OD, Surugau N, Kansedo J, Panchal SK, Brown L. Plant-based functional foods from Borneo. *Nutrients* (2025);17. <https://doi.org/10.3390/nu17020200>
- [11] Al-Sheraji SH, Ismail A, Manap MY, Mustafa S, Yusof RM, Hassan FA. Fermentation and non-digestibility of *Mangifera pajang* fibrous pulp and its polysaccharides. *J Funct Foods* (2012);4:933–40. <https://doi.org/10.1016/j.jff.2012.07.001>
- [12] Ahmad S, Sukari MA, Ismail N, Ismail IS, Abdul AB, Abu Bakar MF, et al. Phytochemicals from *Mangifera pajang* Kosterm and their biological activities. *BMC Complement Altern Med* (2015);15:1–8. <https://doi.org/10.1186/s12906-015-0594-7>
- [13] Ibrahim M, Nagendra Prasad K, Ismail A, Azlan A, Hamid AA. Physiochemical composition and antioxidant activities of underutilized *Mangifera pajang* fruit. *African J Biotechnol* (2010);9:4392–7. <https://doi.org/10.5897/AJB10.452>
- [14] Ngerensaengsaruy C. Lectotypifications of three names in *Garcinia*, synonymy of *Garcinia pedunculata* and detailed descriptions of three species in *Garcinia* section. *Diversity* (2022);14. <https://doi.org/10.3390/d14070556>
- [15] Sutomo S, Kamali DN, Arnida A, Normaidah N, Sriyono A. Pharmacognostic study and antioxidant activity of *mundar* (*Garcinia forbesii* king.) leaves from banua botanical gardens of South Kalimantan. *Borneo J Pharm* (2020);3:209–15. <https://doi.org/10.33084/bjop.v3i4.1541>
- [16] Haris MAM, Sani SA. Antioxidant screening of *Garcinia Forbesii* originated from Sabah. *J Phys Conf Ser* (2022);2314. <https://doi.org/10.1088/1742-6596/2314/1/012031>
- [17] Rosyidah K, Rizki MA, Astuti MD, Rodiansono. Toxicity of n-hexane extract of *mundar* (*Garcinia forbesii* King) pericarp. *BIO Web Conf* (2020);20:03004. <https://doi.org/10.1051/bioconf/20202003004>
- [18] Afiqah N, Abdul H, Shamsudin R, Ariffin SH. Physical properties of full-ripe *dabai* (*canarium odontophyllum* miq. variety song) at different fractions. *Pertanika J Sci Technol* (2024);32:725–39. <https://doi.org/10.47836/pjst.32.2.13>
- [19] Shamsudin R, Ariffin SH, Abdullah WNZZ, Azmi NS, Halim AAA. Quality evaluation of color and texture of the *Dabai* fruit (*Canarium odontophyllum* Miq.) at different temperatures and times of blanching. *Pertanika J Sci Technol* (2022);30:2427–38. <https://doi.org/10.47836/pjst.30.4.07>
- [20] Mundi M, Rawi MH, Saupi N, Sarbini SR. Mini-review: Phytology of *Dabai* (*Canarium odontophyllum*) as a potential functional food. *Food Res* (2022);6:296–303. [https://doi.org/10.26656/fr.2017.6\(1\).775](https://doi.org/10.26656/fr.2017.6(1).775)
- [21] Chua HP, Nicholas D, Adros Yahya MN. Physical properties and nutritional values of *dabai* fruit (*Canarium odontophyllum*) of different genotypes. *J Trop Agric Fd Sc* (2015);43:1–10.
- [22] Tan CX, Azlan A. Nutritional, phytochemical and pharmacological properties of *Canarium odontophyllum* miq. (*Dabai*) fruit. *Pertanika J Sch Res Rev* (2016);2:80–94.
- [23] Yuniastuti E, Yuliana A. Genetic diversity of *Matoa* (*pometia pinnata*) species based on RAPD markers. *Sabroa J Breed Genet* (2023);55:1941–9.
- [24] Suzuki T, Nagata M, Kagawa N, Takano S, Nahrowi, Nomura J. Anti-obesity effects of *matoa* (*Pometia pinnata*) fruit peel powder in high-fat diet-fed rats. *Molecules* (2021);26. <https://doi.org/10.3390/molecules26216733>
- [25] Sholiha FU, Yuniastuti E, Hartati S. The *matK* gene analysis in five types of *matoa* (*Pometia pinnata* J. R. Forst. and ; G. Forst) based on the pericarp colour. *J Appl Biol Biotechnol* (2024);12:54–8. <https://doi.org/10.7324/JABB.2024.167495>
- [26] Lim TK. *Pometia pinnata*. In: Lim TK, editor. *Edible Med. non-medicinal plants*, vol. 6, Dordrecht: Springer; (2013), p. 92–6. <https://doi.org/10.1007/978-94-007-5628-1>
- [27] Kutoi CJ, Yen KH, Seruji NMU. Pharmacology evaluation of *Litsea garciae* (Lauraceae). BEIAC 2012 - 2012 IEEE Business, *Eng Ind Appl Colloq* (2012);31–3. <https://doi.org/10.1109/BEIAC.2012.6226075>
- [28] Amit Z, Zinyin L. A mini review on the nutritional compositions and pharmacological properties of *litsea garciae*. *Malaysian Appl Biol* (2021);50:29–39. <https://doi.org/10.55230/mabjournal.v50i1.10>
- [29] Tang YP, Linda BLL, Franz LW. Proximate analysis of *Artocarpus odoratissimus* (Tarap) in. *Int Food Res J* 2013;20:409–15.
- [30] Noorfarahzilah M, Jau-Shya L, Mansoor AH, Jahurul MHA, Umi Hartina MR, Zainol MK, et al. Physicochemical properties of *tarap* (*Artocarpus adoratisimus*) starch. *Food Res* (2020);4:602–11. [https://doi.org/10.26656/fr.2017.4\(3\).337](https://doi.org/10.26656/fr.2017.4(3).337)
- [31] Mikail MA, Ahmed IA, Ibrahim M, Hazali N, Abdul Rasad MSB, Abdul Ghani R, et al. *Baccaurea angulata* fruit inhibits lipid peroxidation and induces the increase in antioxidant enzyme activities. *Eur J Nutr* (2016);55:1435–44. <https://doi.org/10.1007/s00394-015-0961-7>
- [32] Lim TK. *Garcinia forbesii*. In: Lim TK, editor. *Edible Med. Non-Medicinal Plants*, Dordrecht: Springer Netherlands; (2012), p. 225–7. https://doi.org/10.1007/978-94-007-4053-2_28

- [33] Ahmed IA, Mikail MA, Ibrahim M. *Baccaurea angulata* fruit juice ameliorates altered hematological and biochemical biomarkers in diet-induced hypercholesterolemic rabbits. *Nutr Res* (2017);42:31–42. <https://doi.org/10.1016/j.nutres.2017.04.012>
- [34] Ahmed IA, Mikail MA, Bin Ibrahim M, Bin Hazali N, Rasad MSBA, Ghani RA, et al. Antioxidant activity and phenolic profile of various morphological parts of underutilised *Baccaurea angulata* fruit. *Food Chem* (2015);172:778–87. <https://doi.org/10.1016/j.foodchem.2014.09.122>
- [35] Chew IYY, Chung HH, Lau MML, Wee BS, Sim SF. *Shorea macrophylla*: Overview of illipe nut producing tree. *Pertanika J Trop Agric Sci* (2022);45:663–75. <https://doi.org/10.47836/pjtas.45.3.08>
- [36] Ramli S, Nor N, Sukri S, Adhwa N, Zulkifli F, Maretta D, et al. Antioxidant activities and protective effects of *shorea macrophylla* leaf and bark extracts. *Pharm Sci Res* (2024);11:34–40. <https://doi.org/10.7454/psr.v11i1.1372>
- [37] Abu Bakar MF, Mohamed M, Rahmat A, Fry J. Phytochemicals and antioxidant activity of different parts of bambangan (*Mangifera pajang*) and tarap (*Artocarpus odoratissimus*). *Food Chem* (2009);113:479–83. <https://doi.org/10.1016/j.foodchem.2008.07.081>
- [38] Wairata J, Fadlan A, Setyo Purnomo A, Taher M, Ersam T. Total phenolic and flavonoid contents, antioxidant, antidiabetic and antiplasmodial activities of *Garcinia forbesii* King: A correlation study. *Arab J Chem* (2022);15:103541. <https://doi.org/10.1016/j.arabjc.2021.103541>
- [39] Ringgit G, Cheong BE, Shah MD, Siddiquee S. Phytochemical composition and antioxidant properties of *Canarium odontophyllum* (Sarawak Olive): A seasonal fruit from Borneo, East Malaysia. *Phytomedicine Plus* (2025);5:100703. <https://doi.org/10.1016/j.phyplu.2024.100703>
- [40] Faustina FC, Santoso F. Extraction of fruit peels of *pometia pinnata* and its antioxidant and antimicrobial activities. *J Penelit Pascapanen Pertan* (2017);11:80–8. <https://doi.org/10.21082/jpasca.v11n2.2014.80-88>
- [41] Khoo HE, Azlan A, Kong KW, Ismail A. Phytochemicals and medicinal properties of indigenous tropical fruits with potential for commercial development. *Evidence-Based Complement Altern Med* (2016);2016. <https://doi.org/10.1155/2016/7591951>
- [42] Ibrahim M, Maryam Abimbola Mikail, Ahmed IA, Ghani RA. Phenolic-rich *Baccaurea angulata* modulates inflammatory biomarkers of atherosclerosis. *J Nutr Metab* (2018);2018:1–7.
- [43] Al-Sheraji SH, Ismail A, Manap MY, Mustafa S, Yusof RM, Hassan FA. Functional properties and characterization of dietary fiber from *mangifera pajang* kort. Fruit pulp. *J Agric Food Chem* (2011);59:3980–5. <https://doi.org/10.1021/jf103956g>
- [44] Mahesh MP, K.A. AA. Bioactive compounds and health benefits. *Introd to Funct Food Sci* (2013);1–20. https://doi.org/10.1007/978-3-319-54528-8_59-1
- [45] Ali Hassan SH, Fry JR, Abu Bakar MF. Phytochemicals content, antioxidant activity and acetylcholinesterase inhibition properties of indigenous *garcinia parvifolia* fruit. *Biomed Res Int* (2013);2013:1–7. <https://doi.org/10.1155/2013/138950>
- [46] Hamzah MH, Zulkefli N, Hamzah AFA, Shamsudin R, Man HC, Ali AHM, et al. Optimization of process parameters using response surface methodology for essential oil extraction from *canarium odontophyllum* kernels by subcritical water treatment Subcritical Water Treatment. *Food Anal Methods* (2024);17:910–29. <https://doi.org/10.1007/s12161-024-02624-7>
- [47] Nyokat N, Yen KY, Hamzah AS, Lim IF, Saaiddin AS. Isolation and synthesis of pinocembrin and pinostrobin from *Artocarpus odoratissimus*. *Malaysian J Anal Sci* (2017);21:1156–61.
- [48] Darina I, Norazlan Shah H, Nurhazni Khir J, Muhammad NO, Mohd NAY, Idris AA, et al. Physicochemical and antioxidant characteristics of *Baccaurea angulata* fruit juice extract. *African J Biotechnol* (2013);12:5333–8. <https://doi.org/10.5897/ajb2013.12989>
- [49] Rakman SA, Assim Z, Ahmad FB. Chemical Assessment and Proximate Composition of *Shorea macrophylla* and *Shorea palembanica* Seed Oil and Oilseeds. *Authorea* (2021);2:3–5.
- [50] Yanty NAM, Marikkar JMN, Shuhaimi M. Effect of fractional crystallization on the composition and thermal properties of Engkabang (*Shorea macrophylla*) seed fat and cocoa butter. *Grasas y Aceites* (2013);64:546–53. <https://doi.org/10.3989/gya.023213>
- [51] Rao SN, Redhwan AI, Ha HC, Nguang SI, Kari A, Yong WS, et al. A Review of borneo buah engkabang (*Shorea macrophylla*) as potential omega-6 lipid source for fish feed. *E3S Web Conf* (2023);442. <https://doi.org/10.1051/e3sconf/202344202034>
- [52] Wong KC, Siew SS. Volatile components of the fruits of bambangan (*mangifera panjang* kostermans) and binjai (*mangifera caesia* jack). *Flavour Fragr J* (1994);9:173–8. <https://doi.org/10.1002/ffj.2730090406>
- [53] Khoo HE, Ismail A. Determination of daidzein and genistein contents in *Mangifera* fruit. *Malays J Nutr* (2008);14:189–98.

- [54] Bakar MFA, Mohamed M, Rahmat A, Burr SA, Fry JR. Cytotoxicity and polyphenol diversity in selected parts of *Mangifera pajang* and *Artocarpus odoratissimus* fruits. *Nutr Food Sci* (2010);40:29–38. <https://doi.org/10.1108/00346651011015890>
- [55] Prasad KN, Chew LY, Khoo HE, Yang B, Azlan A, Ismail A. Carotenoids and antioxidant capacities from *Canarium odontophyllum* Miq. fruit. *Food Chem* (2011);124:1549–55. <https://doi.org/10.1016/j.foodchem.2010.08.010>
- [56] Pin CH, Daniel N, Mos S. Phenolic and flavonoid contents and antioxidant activities of selected dabai (*Canarium odontophyllum*) genotypes. *J Trop Agric Fd Sc* (2014);42:105–14
- [57] Hanafi, Irawan C, Sirait SM, Sulistiawaty L, Setyawati SR. Toxicity test with bslt (brine shrimp lethality test) method on methanol, ethyl acetate extract, hexane on seeds and rind of matoa extract (*pometia pinnata*). *Orient J Chem* (2020);36:1143–7. <https://doi.org/10.13005/ojc/360618>
- [58] Irawan C, Hanafi H, Sulistiawaty L, Rochaeeni H. Phytochemistry and total phenolic content of methanol extract of *Pometia pinata* J.R. Forst. & G. Forst. fruit flesh from Papua, Indonesia. *Trop Plant Res* (2017);4:401–4. <https://doi.org/10.22271/tpr.2017.v4.i3.053>
- [59] Raduan SZ, Ahmed QU, Kasmuri AR, Rusmili MRA, Mia MAR, Wan Sulaiman WMA, et al. Antioxidant capabilities of *Litsea garciae* bark extracts and their relation to the phytochemical compositions. *Malaysian Appl Biol*. (2022);51:99–118. <https://doi.org/10.55230/MABJOURNAL.V51I1.2038>
- [60] Wulandari I, Kusuma IW, Kuspradini H. Antioxidant and antibacterial activity of *Litsea garciae*. *IOP Conf Ser Earth Environ Sci* (2018);144. <https://doi.org/10.1088/1755-1315/144/1/012024>
- [61] Hazali N, Mohd Affiq MA, Muhammad I, Masri M. Determination of phytochemicals and vitamin content of underutilized *Baccaurea angulata* fruit. *J Pharmacogn Phytochem* (2015);4:192–6.
- [62] Redhwan Al, Khairulnizam NANM, Zuki NAM, Aminudin NH, Komilus CF. Replacement of fish oil with engkabang butter oil (*shorea macrophylla*): Effects on growth performance of javan mahseer (*Tor tambra*). *Malaysian Appl Biol* (2023);52:73–80. <https://doi.org/10.55230/mabjournal.v52i5.fisas07>
- [63] Ikram EHK, Eng KH, Jalil AMM, Ismail A, Idris S, Azlan A, et al. Antioxidant capacity and total phenolic content of Malaysian underutilized fruits. *J Food Compos Anal* (2009);22:388–93. <https://doi.org/10.1016/j.jfca.2009.04.001>
- [64] Prasad KN, Hassan FA, Yang B, Kong KW, Ramanan RN, Azlan A, et al. Response surface optimisation for the extraction of phenolic compounds and antioxidant capacities of underutilised *Mangifera pajang* Kosterm. peels. *Food Chem* (2011);128:1121–7. <https://doi.org/10.1016/j.foodchem.2011.03.105>
- [65] Ahmad Hasan Salahuddin M, Idris S, Mirad R. Natural antioxidant properties of selected wild *Mangifera* species in Malaysia. *J Trop Agric Fd Sc* (2016);44:63–72.
- [66] Ishak SF, Rajab NF, Basri DF. Analysis of GC-MS from acetone extract of *Canarium odontophyllum* miq stem bark (Dabai). *Biomed Pharmacol J* (2024);17:1009–20. <https://doi.org/10.13005/bpj/2918>
- [67] Razali NSM, Wenyin B, Arjunan RD, Hashim H, Abdullah A. Total phenolic content and antioxidant activities of date fruit extracts. *Malaysian Appl Biol* (2019);48:103–8.
- [68] Lee MS, Chyau CC, Wang CP, Wang TH, Chen JH, Lin HH. Flavonoids identification and pancreatic beta-cell protective effect of lotus seedpod. *Antioxidants* (2020);9:1–23. <https://doi.org/10.3390/antiox9080658>
- [69] Wiraswati H, Ekawardhani S, Rohmawaty E, Laelalugina A, Zuhrotun A, Hendriani R, et al. Antioxidant, anti inflammation, and antifibrotic activity of ciplukan (*Physalis angulata* L). extract. *J Inflamm Res* (2024);17:6297–306. <https://doi.org/10.2147/jir.s470318>
- [70] Anju T, Kumar A. Traditional ecological knowledge and medicinal plant diversity usage among the Mullu Kuruman tribes of Wayanad district of Kerala, India and its implications for biodiversity conservation in the face of climate change. *Trees, For People* (2024);16:1–15. <https://doi.org/10.1016/j.tfp.2024.100595>
- [71] Sudomo A, Leksono B, Tata HL, Rahayu AAD, Umroni A, Rianawati H, et al. Can agroforestry contribute to food and livelihood security for Indonesia's smallholders in the climate change era? *Agric* (2023);13. <https://doi.org/10.3390/agriculture13101896>
- [72] Nursamsu, Nuraini, Sarjani TM, Mardudi. The use of medicinal plants in the Aneuk Jamee tribe in Kota Bahagia, South Aceh District, Indonesia. *Biodiversitas* (2024);25:2524–40. <https://doi.org/10.13057/biodiv/d250622>
- [73] Sultan MTH, Shahar FS, Zain MIM, Komoo I. A systematic review of the role of integrated farming and the participation of universities in ensuring food security: Malaysia's effort. *Ital J Food Saf* (2024);13. <https://doi.org/10.4081/ijfs.2024.11854>
- [74] Opolot HN, Isubikalu P, Obaa BB, Ebanyat P. Influence of university entrepreneurship training on farmers' competences for improved productivity and market access in Uganda. *Cogent Food Agric* (2018);4. <https://doi.org/10.1080/23311932.2018.1469211>
- [75] Borelli S, Conigliaro M, Quaglia S, Salbitano F. Urban and Peri-urban agroforestry as multifunctional land use. *Agrofor Anecdotal to Mod Sci* (2018):705–24. https://doi.org/10.1007/978-981-10-7650-3_28

- [76] Jamnadass RH, Dawson IK, Franzel S, Leakey RRB, Mithfer D, Akinnifesi FK, et al. Improving livelihoods and nutrition in sub-saharan africa through the promotion of indigenous and exotic fruit production in smallholders' agroforestry systems: A review. *Int For Rev* (2011);13:338–54. <https://doi.org/10.1505/146554811798293836>
- [77] Thow AM, Priyadarshi S. Aid for Trade: an opportunity to increase fruit and vegetable supply. *Bull World Health Organ* (2013);91:57–63. <https://doi.org/10.2471/BLT.12.106955>