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REVIEW ARTICLE

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Marang fruit (*Artocarpus Odoratissimus*) waste: A promising resource for food and diverse applications: A review of its current status, research opportunities, and future prospects

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Abstract

Marang fruit is commonly found and available in various Southeast Asian regions, notably in countries such as Malaysia, the Philippines, and Indonesia. Marang fruit waste, despite its promising potential, remains underutilized in various applications. This review article explores the potential of Marang fruit waste as a valuable resource for various applications, with a focus on its utilization in the food industry, including seed flour, starch, snacks, and essential bioactive compounds. Beyond the food sector, the article also investigates its applications as biosorbents/adsorbents and an energy source. The study identifies promising research opportunities such as investigating its potential as a fuel source, as well as for the production of cellulose and nanocellulose which is now gaining relevant attention in various industries. However, the seasonal availability of Marang fruit and its limited distribution in specific Southeast Asian regions present challenges. This article aims to provide a comprehensive understanding of the current status, highlight the areas that require further investigation, and future prospects of Marang fruit waste, highlighting its significance as a sustainable resource with multifaceted applications.

KEYWORDS

agricultural wastes, circular economy, Marang fruit wastes, utilization, value-adding

1 | INTRODUCTION

Marang, scientifically known as *Artocarpus odoratissimus*, is a tropical fruit produced in the Philippines, notably in Mindanao's marginal and mountainous locations such as the Zamboanga Peninsula (Martinez & Perez, 2016). It is found to be endemic to Borneo Island, and this species has been introduced in the Philippines (Soepadmo & Saw, 2000). The fruit is highly regarded in the region, particularly in Sabah, Malaysia, where it is locally known as 'tarap' (Abu Bakar et al., 2009). Marang trees, a tree that bears Marang fruit, may reach a height of 20–25 m and are normally cultivated from seed; fruiting begins when the tree is around 4 to 5-year-old (Noorfarahzilah et al., 2017). In terms of morphology, the fruit has an intermediate form between jackfruit and breadfruit (Galang, 1955; Subhadrabandhu, 2001). The fruit is composed of different nutritional components such as carbohydrates, protein, fats, crude fiber, ash, potassium, calcium, sodium, phosphorus, iron, retinol, beta-carotene, vitamin A, vitamin B1 (thiamine), vitamin B2 (riboflavin), vitamin B3 (niacin), and vitamin C (ascorbic acid) (Tang et al., 2013). Marang fruit has several economic and nutritional benefits, the plant has numerous advantages as a successful multifunctional crop for fruit and timber production (de Almeida Lopes et al., 2018). It is also an excellent source of minerals, which can help with stroke, blood pressure, heart and renal diseases, anxiety, and stress, as well as improve muscular strength, metabolism, water balance, electrolytic processes, and the neurological system (Martinez & Perez, 2016).

According to the Philippine Statistics Authority PSA (2016), the estimated volume of Marang fruit production in the country reaches up to 43.5 metric tons in 2014. This means that more than 26 metric tons of this product are discarded that year as the flesh only covers around

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40%, while 60% of the total weight is not utilized and is considered waste (Abu Bakar et al., 2009). Improper disposal of the substantial peel and core residues generated from Marang fruit poses potential environmental concerns, and if these waste materials are not appropriately managed, they can indeed lead to significant environmental problems (Selvaraju & Bakar, 2017). According to Rifna et al. (2023), the most commonly employed method for fruit waste disposal is landfill, incineration, and open burning. However, this method of disposal poses significant environmental problems, such as water and soil pollution, the greenhouse effect, eutrophication, and global warming, if not properly managed due to its high biodegradability and fermentability (de Medeiros et al., 2020). Furthermore, these methods or approaches may result in secondary generation wastes and other problems (Nirmal et al., 2023). In addition, fruit wastes are renewable and viable resources that could be valorized in accordance with the concept of a "circular economy" to produce commodities with a high market value (Chew et al., 2017).

Compounds derived from *Artocarpus* species were shown to demonstrate a wide variety of biological activities, including antibacterial, antitubercular, antiviral, antifungal, antiplatelet, antiarthritic, tyrosinase inhibitory, and cytotoxic properties (Jagtap & Bapat, 2010). Studies done in the past have shown that different species of *Artocarpus* are abundant in phenolic substances such as flavonoids, stilbenoids, and arylbenzofurons (Yen et al., 2017). Moreover, these phenolic substances have been associated with potent antioxidant properties and have shown potential in preventing chronic diseases, such as cancer, cardiovascular diseases, and neurodegenerative disorders (Pandey & Rizvi, 2009; Vauzour et al., 2010). The utilization of Marang fruit waste presents an opportunity to harness these beneficial compounds and transform them into value-added products.

In previous years, only rare studies have been conducted to valorize Marang fruit waste, rendering it underutilized and thus providing significant potential for valorization. Some of these few studies that focus on exploring the potentialities of Marang fruit wastes include the development of low-cost biosorbent from Marang peel (Lim et al., 2015), flour from Marang seed (Masri et al., 2017), adsorbent from cellulose extracted from Marang leaves (Zaidi, Lim, Usman, et al., 2018), and adsorbent from Marang core (Dahri, Lim, et al., 2017). However, despite the growing interest in the utilization of *Artocarpus* species, including the Marang fruit, there is still a need for a comprehensive review that examines the potential utilization of Marang fruit waste and explores future prospects and research opportunities. By consolidating existing knowledge and identifying research gaps, this review aims to contribute to the advancement of sustainable utilization strategies for Marang fruit waste and provide valuable insights for further exploration in this field. In response to the pressing need for eco-friendly solutions and effective waste management, this review article serves as a critical foundation for researchers, policymakers, and industries. The need for a dedicated review in this field arises from the limited availability of consolidated information, the increasing demand for eco-friendly alternatives, and the urgent call for strategies to minimize food waste and environmental impact. This article fills a crucial knowledge gap by presenting a holistic view of the current state of Marang fruit waste utilization, underscoring the urgency of sustainable practices and highlighting areas where further investigation and collaboration are essential for the advancement of this field.

2 | COMPOSITION OF MARANG FRUIT

As shown in Figure 1, the Marang fruit is composed of four main parts which are the husk/peel, flesh, seed, and core. The husk/peel of the Marang fruit is typically thick and fibrous, providing protection to the inner parts of the fruit. The flesh, which is the edible part, is tasty and soft, with a distinct aroma and rich flavor (Jonatas et al., 2020; Masri et al., 2017). The seed, enclosed within the flesh, is large and usually not consumed, but it can be utilized for its oil content and starch (Ismail et al., 2022). Lastly, the core refers to the central portion of the fruit, which is often discarded as it is not typically consumed due to its fibrous and tough nature. The flesh of the fruit represents around 50%–60% of the total weight of the fruit while the remaining 40%–50% are the pulp, husk/peel, and seed which are usually discarded (Abu Bakar et al., 2009).

The composition of the Marang fruit plays a crucial role in determining its potential applications and utilization. The fruit is known for its rich nutritional profile and diverse bioactive compounds, making it an attractive resource for various industries. Several studies have investigated the composition of the Marang fruit, providing insights into its chemical constituents and nutritional value. Tang et al. (2013) investigated the nutrient composition of Marang fruit flesh. From the results of their study (in Table 1), it can be seen that the nutrient composition of Marang fruit is characterized by its high moisture content (67.9%–73.4%) and moderate carbohydrate levels (12.0–25.2 g). It is also a good source of minerals such as potassium, with values ranging from 176 to 298 mg/100 g. Potassium plays a crucial role in maintaining proper fluid balance, regulating blood pressure, supporting muscle and nerve function, and promoting overall cardiovascular health (Udensi & Tchounwou, 2017). The fruit is relatively low in fiber and provides varying amounts of essential minerals such as iron, zinc, and manganese. These essential minerals, including iron which aids in oxygen transport (Abbaspour



FIGURE 1 Component of fresh Marang fruit.

et al., 2014), zinc that supports immune function and wound healing (Lin et al., 2017), and manganese known for its role in bone health and antioxidant defense (Avila et al., 2013), contribute to the overall nutritional value of the fruit.

Similarly, Masri et al. (2017) conducted a study on the nutrient composition of Marang seeds, revealing that they are a valuable source of dietary fiber, protein, and fat. The findings of their study highlight the potential nutritional benefits that can be derived from incorporating Marang seeds into our diet. From the study of Ismail et al. (2021), the flesh and seeds of Marang are rich in carbohydrates, with 82.70% and 59.20%, respectively. Additionally, potassium was the major mineral component found in all parts of the fruit, ranging from 905.61 mg/100 g (seeds) to 1210.40 mg/100 g (flesh), while the flesh part exhibited high levels of fructose (26.7 g/100 g), glucose (25.38 g/100 g), and vitamin B1 (11.07 mg/100 g). The leaves of the fruit also contain various bioactive compounds such as alkaloid, flavonoid, phenolic, and steroid/triterpenoid compounds (Naspiah & Pratama, 2021). From the study of Ragasa et al. (2014), the chemical investigation of the dichloromethane extract of *Artocarpus altilis* leaves revealed the presence of β-sitosterol, unsaturated triglycerides, squalene, polyprenol, lutein, and unsaturated fatty acids. Similarly, the dichloromethane extract of *A. odoratissimus* provided β-sitosterol, unsaturated fatty acids, and hydrocarbons from the fruit rind, as well as unsaturated fatty acids from the flesh of the fruit and seeds.

TABLE 1 Nutrient composition of Marang fruit flesh (Tang et al., 2013).

Component	Nutrient per 100 g
Moisture (%)	67.9–73.4
Ash (g)	0.6–0.8
Carbohydrate (g)	12.0–25.2
Protein (g)	1.31–1.51
Fiber (g)	0.90–1.13
Fat (g)	-
Energy (kcal)	90.7–100.6
K (mg/100 g)	176–298
Na (mg/100 g)	1.15–1.70
Mg (mg/100 g)	0.48–1.35
Fe (mg/100 g)	14.8–31.3
Mn (mg/100 g)	0.29–0.53
Cu (mg/100 g)	0.02–0.93
Zn (mg/100 g)	0.17–0.45
Cd (mg/100 g)	0.0104–0.0149

3 | CURRENT UTILIZATION OF MARANG FRUIT WASTES

The current status of the utilization of Marang fruit wastes is illustrated in Figure 2. It has gained considerable attention in recent years due to its potential for various applications. It does not only address the problem of waste disposal, but it also follows the concept of circular economy. Several studies have explored innovative approaches for the effective utilization of these wastes, aiming to minimize their environmental impact and enhance their value. One notable application is the extraction of bioactive compounds from Marang fruit peels and cores. One study by Abu Bakar et al. (2009) identified the presence of bioactive compounds such as phenolics, flavonoids, and antioxidants from the flesh, kernel, and husk of the fruit, highlighting their potential for use in functional food and nutraceutical industries (Yulianti et al., 2022). Moreover, Marang fruit wastes have been also investigated for their potential for the production of eco-friendly biosorbents or adsorbents

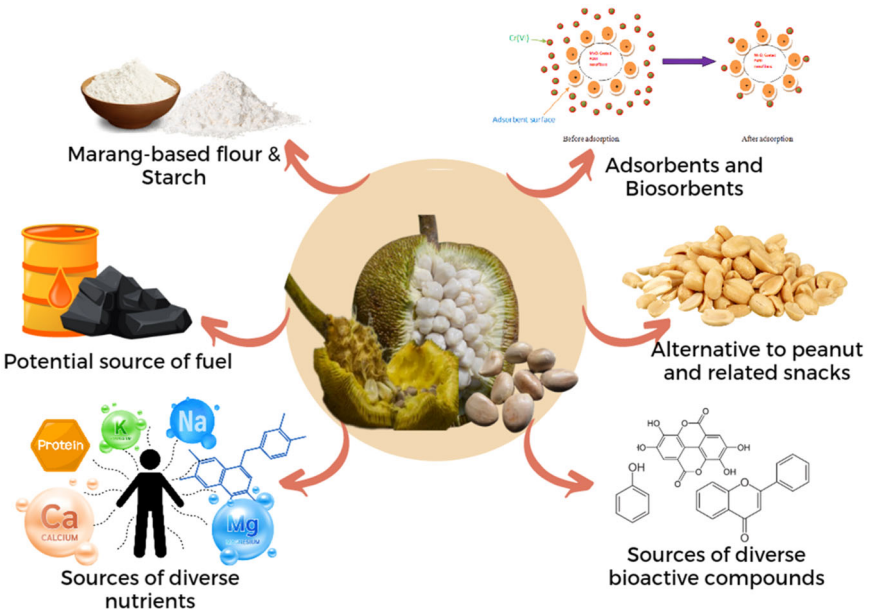


FIGURE 2 Current status of Marang fruit waste utilization.

for the removal of various toxic compounds, and heavy metals (Lim et al., 2016; Zaidi et al., 2018a, 2019). The potential of Marang fruit waste as a source of energy in the form of briquettes has been characterized by Hesty (2012) where findings from their study revealed the potential of Marang fruit wastes as a renewable source for the development of briquettes. Other studies have focused to characterize and evaluate the potential of Marang seeds as raw materials for making flour (Masri et al., 2012, 2017) and a potential source of various bioactive compounds (González-Aguilar et al., 2008; Kumar et al., 2021; Patra et al., 2022), which hold great potential and interest for the food and pharmaceutical industries.

3.1 | Marang-based flour

The current status of utilizing Marang fruit and its waste for developing flour has gained significant attention due to its potential in various applications particularly in the food industry. Marang fruit waste flour has shown promise as a functional ingredient in food products, providing enhanced nutritional value, unique flavor profiles, and potential health benefits. Research on the utilization of Marang fruit and its waste flour is ongoing, exploring their applications in the development of functional foods, nutraceuticals, and food supplements. Additionally, efforts are being made to optimize processing techniques, improve product quality, and develop innovative value-added products from Marang fruit and its waste flour, contributing to the sustainable utilization of this tropical fruit resource. Generally, there are four major unit operations involved in the production of flour from Marang by-products, as illustrated in Figure 3. The initial procedure is the sample preparation, in which the desired component of the Marang fruit is separated from other components, cleaned, and washed. The prepared component of the fruit, such as the seed, will then undergo an oven-drying process, usually at 40°C for 2–3 days. The dried samples will then undergo a size reduction to achieve its powdered state, usually performed using a blender. The ground samples will then be sieved using a sieve size <250 μm or a sieve size <200 μm (Masri et al., 2012, 2017). Masri et al. (2017) developed flour from Marang seeds and subsequently investigated its nutritional content. The proximate analysis results demonstrated that the flour contained 49.65% carbohydrate, 15.60% crude fat, 12.3% crude fiber, 8.8% crude protein, 1.17% ash, and 12.5% moisture. The analysis revealed the presence of several minerals in the flour, with Potassium being the most abundant, followed by magnesium, calcium, and sodium in Marang seed flour. Based on their findings, the researchers concluded that Marang seed flour exhibits significant potential for utilization in composite flour formulations as a valuable ingredient in the food industry. Likewise, Masri et al. (2012) studied the nutrient composition and other properties of flour derived from Marang fruit. Results from their study revealed that the proximate analysis of Marang flour revealed a moisture content of 10.29%, protein content of 6.58%, ash content of 2.84%, crude fiber content of 2.65%, fat content of 1.89%, carbohydrate content of 75.75%. The particle size distribution ranged from 125 to 63 μm, and the bulk density was 0.51 g/mL. Marang flour demonstrated a lightness value (L*) of 70.64, redness value (a*) of 5.62, and yellowness value (b*) of 22.02, indicating its potential as a new food ingredient with desirable characteristics.

3.2 | Source of bioactive compounds

Bioactive compounds encompass a diverse range of nutrients and non-nutrients found within the food matrix, derived from both plant and animal sources, which have the ability to elicit physiological effects that extend beyond their conventional nutritional roles (Cazarin et al., 2021). Bioactive compounds serve as a valuable resource for the formulation of nutritional supplements, food additives, and functional foods, offering potential benefits for human health and well-being (Dimou et al., 2019). The most notable bioactive compounds that have been quantified in the flesh, seed, and husk of the Marang fruit are arranged as encapsulated in Table 2. As indicated by Ali et al. (2022), agricultural residues have the potential to serve as a valuable source of bioactive compounds with diverse health-promoting effects. These bioactive chemicals have demonstrated various beneficial properties including antitumor, cardioprotective, antiviral, antibacterial, and antiobesity activities, among others. Recent studies have unlined the potential of fruit wastes as a source of various bioactive compounds (González-Aguilar et al., 2008; Kumar et al., 2021; Patra et al., 2022). Deng et al. (2012) also emphasized the importance of utilizing fruit wastes as sources of bioactive compounds, as they may offer considerable economic benefits and have become increasingly attractive. It can also be an effective approach from the perspective of sustainability and a circular economy, addressing the global goal of achieving "zero waste" in the environment (Lucarini et al., 2021).

In previous years, bioactive compounds derived from Marang fruit wastes have gained significant attention due



FIGURE 3 Process flow for the production of flour from Marang fruit by-products.

TABLE 2 Bioactive compounds quantified in each part of the Marang fruit.

Bioactive compounds	Component of the fruit	Level of bioactive compound	References
Total polyphenols	Flesh	4.39 mg GAE/g	Abu Bakar et al. (2009)
		3.53 mg GAE/g	Abu Bakar et al. (2015)
	Seed	14.67 mg GAE/g	Abu Bakar et al. (2009)
		13.72 mg GAE/g	Abu Bakar et al. (2015)
	Seed	18.67 mg GAE/g	Ismail et al. (2022)
	Husk	42.38 mg GAE/g	Abu Bakar et al. (2015)
Antioxidant properties	Flesh	17.92 μM/g	
		5.34 mg/g	
	Seed	68.06 μM/g	
		7.61 mg/g	
	Husk	378.93 μM/g	
		26.11 mg/g	
	Flesh	2.44 mg AEAC/g	Abu Bakar et al. (2009)
	Seed	13.69 mg AEAC/g	
Total flavonoids	Flesh	1.08 mg RE/g	
		1.23 mg CE/g	Abu Bakar et al. (2015)
	Seed	12.64 mg QE/g	Ismail et al. (2022)
		3.65 mg RE/g	Abu Bakar et al. (2009)
		10.18 mg CE/g	Abu Bakar et al. (2015)
	Husk	36.78 mg CE/g	
Total carotenoids	Flesh	0.79 mg ßC/g	
	Seed	0.67 mg ßC/g	
	Husk	0.86 mg ßC/g	
Total anthocyanin	Flesh	11.02 mg c-3-gE/100 g	Abu Bakar et al. (2009)
	Seed	3.80 mg c-3-gE/100 g	

Abbreviations: mg AEAC/g, mg ascorbic acid equivalent antioxidant capacity (AEAC) in 1 g of dry sample; mg c-3-gE/100 g, mg cyanidine-3-glucoside equivalent in 100 g of dry sample; mg CE/g, mg catechin equivalents in 1 g of dry sample (mg CE/g); mg GAE/g, mg gallic acid equivalent in 1 g of dry sample; mg RE/g, mg rutin equivalent in 1 g of dry sample; mg ßC/g, mg ß-carotene equivalents in 1 g of dry sample (mg ßC/g); mg/g, mg ascorbic acid equivalent antioxidant capacity (AEAC) in 1 g of dry sample; μM/g, μM ferric reduction to ferrous in 1 g of dry sample.

to their intrinsic characteristic as a rich source of various bioactive compounds. Jonatas et al. (2020) explored the potential of the Marang fruit in pharmaceutical agent applications by investigating the different phytochemicals contained and the vitro antidiabetic activity of the different parts of the fruit. In their study, they employed thin-layer chromatography for phytochemical screening of the phenolics and flavonoids from the husk/peel, pulp, and seeds of the fruit. These bioactive compounds were known to be the principal component responsible for various antidiabetic activities (Ong & Khoo, 2000). Findings obtained revealed that extracts from different parts of the Marang fruit contain phenols and flavonoids and were potent inhibitors of the alpha-glucosidase enzyme. Among the extracts, the fruit peel extract of Marang exhibited the highest activity (IC50 = 48.19 μg/mL) compared to the seed extract, pulp extract, and the standard drug acarbose ($p = 0.035$). The fruit waste, including the peel and seeds, displayed strong inhibitory effects on the alpha-glucosidase enzyme due to their abundant phenols and flavonoids. Likewise, Abu Bakar et al. (2009) studied the phytochemical and antioxidant activity of the seed and flesh of the fruit. Phenolic and flavonoid compounds possess antioxidant, anticancer, cardioprotective, and antibacterial properties, making them promising candidates for applications in the pharmaceutical and medical industries (Sun & Shahrajabian, 2023; Tungmunnithum et al., 2018). The experiment showed that the peel of Marang had a higher amount of total phenolic content (14.67 mg GAE/g) compared to the flesh (4.39 mg GAE/g). Additionally, the seed of Marang had a higher total flavonoid content compared to the flesh. On the other hand, the flesh of Marang exhibited a higher total anthocyanin content compared to the seed. These findings highlight the variations in bioactive compounds among different parts of the Marang fruit, which may have implications for its potential applications in the food and pharmaceutical

industries. In the study conducted by Bakar (2010), the potential of this fruit's chemopreventive and chemotherapeutic properties was investigated, leading the authors to suggest that both the fruit and its by-products hold great promise for use in pharmaceuticals, nutraceuticals, and various food products.

3.3 | Biosorbent or adsorbent

Biosorbents and adsorbents play a crucial role in environmental remediation and water treatment processes. These materials possess the ability to selectively bind and remove various contaminants from aqueous solutions, making them highly desirable for sustainable purification technologies. The utilization of agricultural wastes for the development of biosorbents and adsorbents presents a promising approach to addressing environmental challenges. The process of biosorption or adsorption offers several advantages, including its simple, minimal carbon footprint, low equipment cost, and the utilization of cost-effective adsorbents during operation (Azmi et al., 2018; Khunt et al., 2019). In the biosorption/adsorption process, the transfer of dye molecules from wastewater to a solid phase occurs, enabling subsequent regeneration of the solid phase for subsequent applications (Yagub et al., 2014). In recent years, researchers have explored unconventional sources for biosorbent and adsorbent development, aiming to utilize agricultural waste products to minimize environmental impact and enhance resource efficiency. Some examples are biosorbents obtained from passion fruit peel (Zhao et al., 2021), pomelo fruit peel (Dinh et al., 2019), lemon fruit peel (Bhatnagar et al., 2010), dragon fruit peel (Jawad et al., 2018), plant leaves (Ighalo & Adeniyi, 2020), flowers (Elangovan et al., 2008; Ghaneian et al., 2012; Khoshsang & Ghaffarinejad, 2018), agricultural and fruit wastes (Cho et al., 2023; Garg et al., 2021; Wang et al., 2022).

In the context of Marang wastes, numerous researchers have studied the potential of wastes generated from Marang fruit such as husk or peel, fruit core, and even leaves as biosorbent or adsorbent. Lim et al. (2012) developed an affordable and low-cost biosorbent derived from the husk of Marang fruit for the removal of methylene blue and methyl violet 2B. These dyes are known to be persistent and toxic, posing environmental and health risks when present in wastewater (Oladoye et al., 2022). Likewise, Lim et al. (2015) also studied the feasibility of an adsorbent derived from Marang husk for the removal of crystal violet dye. The results indicated a strong affinity between the adsorbent and the dye, with enhanced adsorption capacity observed after treatment with NaOH. The adsorption process followed the Langmuir isotherm model, with a maximum adsorption capacity of 118 mg g^{-1} for untreated husk and 195 mg/g for NaOH-treated skin. The kinetics studies supported pseudo-second-order and intraparticle diffusion mechanisms, while the thermodynamic analysis confirmed the spontaneous and endothermic nature of the sorption process. From the study of Dahri, Kooh, et al. (2017), Marang husk and oxalic-acid-modified husk demonstrated effective removal of brilliant green dye from aqueous solutions, with maximum adsorption capacities of 174 mg/g and 275 mg/g, respectively. The adsorption process was influenced by factors such as pH, contact time, and initial dye concentration, and the kinetics study revealed that pseudo-second-order kinetics and film diffusion played significant roles in the adsorption mechanisms. In the study of Anisuzzaman et al. (2019), it was found that Marang husk-based activated carbon demonstrated promising potential for the removal of ammonium ions from wastewater, with an adsorption capacity of 1.858 mg/g. The AC exhibited a high surface area of 1372.51 m^2/g, and the adsorption process followed the Langmuir isotherm model and Pseudo-second order kinetics, highlighting its efficacy as a viable adsorbent for wastewater treatment.

Aside from the Marang husk, the core of the fruit has been also utilized for the development of biosorbent/adsorbent. For instance, Dahri, Kooh, et al. (2017) studied the potential of the Marang core as an adsorbent for the removal of crystal violet dye from an aqueous solution. Researchers found that the Marang core demonstrated excellent adsorption capacity for the removal of crystal violet (CV) dye from aqueous solutions, with a maximum monolayer adsorption capacity of 217 mg/g. The Langmuir isotherm model provided the best fit for the experimental data, and thermodynamic analysis revealed that the adsorption process was feasible and endothermic. The findings suggest that film diffusion and the pseudo-second-order model are key factors influencing the adsorption mechanism of CV onto TC. Similarly, Lim et al. (2012) explored the potential of Marang core as biosorption of cadmium (II) and copper (II) ions from aqueous solution. These heavy metals exhibit significant toxicity and carcinogenic properties, and their consumption has been linked to the development of diverse diseases and disorders (Huang et al., 2018; Yavuz et al., 2011). Results from their study revealed that the Marang fruit core demonstrated efficient biosorption of Cu (II) and Cd (II) ions, with enhanced performance upon acid treatment and minimal influence from nonreacting ions.

From the other part of the fruit, Kooh et al. (2017) studied the capability of the stem axis of the fruit as a possible source of adsorbent for the removal of methyl violet 2B (MV). Results from their study revealed that the adsorption process is influenced by electrostatic and hydrophobic interactions, as indicated by the effects of pH and ionic strength. The Langmuir model demonstrates a high adsorption capacity (q_m) of 263.7 mg/g, and thermodynamic analysis confirms the spontaneous, endothermic nature of the adsorption system. Additionally, the regenerated spent adsorbent maintains a comparable adsorption capacity even after multiple washing cycles, highlighting its potential for practical applications.

From the traditional sense, Marang leaves are not generally considered fruit wastes. Marang leaves have been also studied for their potential as biosorbent or adsorbent in recent years. Zaidi et al. (2019) investigated the enhanced adsorption of malachite green dye using base-modified Marang leaves as adsorbents. The results from their study revealed that the modification of Marang leaves with sodium hydroxide (NaOH) led to a significant

increase in the monolayer adsorption capacity from 254.9 to 422.0 mg/g based on the Langmuir model, and a threefold increase based on the Sips model. The finding also provides valuable insights into the adsorption process, including the types of reactions and the strength of attractions between the adsorbent and adsorbate, along with an examination of various influencing parameters in adsorption. The development of adsorbent derived from cellulose extracted from Marang leaves was studied by Zaidi et al. (2018b). Results revealed that cellulose from the leaves of Marang exhibited potential as a low-cost and effective adsorbent as it was found to have a maximum adsorption capacity of 187 and 239 mg/g for methyl violet and crystal violet, sequentially. Other related studies were also conducted to enhance the adsorption of Pb (II) from aqueous solutions (Zaidi et al., 2018c), to study the adsorption of malachite green dye using artificial neural network modeling (Zaidi, Lim, Usman, et al., 2018), to develop an adsorbent for the removal of toxic rhodamine B dye (Zaidi, Lim, Priyantha, et al., 2018), to investigate the adsorption of toxic violet dye (Mohamad Zaidi et al., 2023), and to remove cationic methyl violet 2B dye (Lim et al., 2016). Collectively, the outcomes from these various studies underscore the potential of Marang leaves as a pivotal component in the formulation of an economical and efficient adsorbent, thereby demonstrating its effectiveness in the removal of toxic heavy metals.

In addition to their adsorption capabilities, the utilization of Marang husk and leaves as biosorbents or adsorbents aligns with the principles of the circular economy by addressing the problem of waste disposal and maximizing the utilization of renewable resources. By repurposing these agricultural by-products, valuable materials can be recovered and used in environmental remediation processes, contributing to a more sustainable approach to waste management. The development of efficient and cost-effective adsorption technologies using Marang waste not only provides a solution for pollutant removal but also promotes the circular use of resources, minimizing environmental impacts and fostering a more sustainable future.

3.4 | Other products

Among the various by-products of Marang, the seeds stand out as a promising resource with significant potential for food product development (Serudin & Tinggal, 1991). These seeds are known to contain various bioactive compounds, including phenolic compounds, flavonoids, and anthocyanins, which offer numerous health benefits and antioxidant properties. According to Serudin and Tinggal (1991), the seed of Marang has comparable carbohydrates, protein, and fat content with cashew nut or peanut with an approximate composition of 28.4, 18.6, and 40.8 g per 100 g of samples, respectively. Marang seeds offer a potential solution for individuals with peanut or cashew nut allergies, as they can serve as a safe and nutritious substitute in various snack applications. Arollado et al. (2018) conducted a study to characterize and compare the physicochemical and pharmacopoeial properties of starches isolated from the seeds of different fruits, including Marang. Among these starches, only rambutan seed starch exhibited comparable and desirable physicochemical and pharmacopoeial properties similar to corn starch.

Ramadhan et al. (2020) explored the extraction of secondary metabolites from Marang using the maceration method with 96% ethanol solvent. The results showed that the 96% ethanol extract of Marang leaves had the highest % yield, followed by the peel and flesh. Phytochemical screening revealed that the 96% ethanol extract contained more secondary metabolites, including phenols, flavonoids, saponins, and alkaloids, compared to maceration using methanol. These findings highlight the potential of Marang wastes as a rich source of bioactive compounds with various biological activities, making them a promising candidate for medicinal applications. In a study conducted by Hesty (2012), the potential of Marang fruit wastes was explored through the fabrication of bio-briquettes. The optimized formula yielded bio-briquettes with desirable characteristics, including a high calorific value (>4700 kcal kg^{-1}), low combustion ashes (<16.20%), moderate water content (11%), minimal sulfur content (0.0098, <1%), and significant compressive strength value (13.7 kg cm^{-2}). These findings suggest that Marang fruit waste can be effectively utilized as a renewable source for briquette production.

4 | RESEARCH OPPORTUNITIES AND CHALLENGES

Research opportunities and challenges in the utilization of Marang fruit wastes present a promising avenue for exploring various applications. One significant area of interest is the potential of Marang fruit waste as a source of fuel. Studies have demonstrated that bio-briquettes fabricated from Marang fruit wastes exhibit desirable characteristics, such as high calorific value and low ash content, making them a viable alternative fuel source (Hesty, 2012). Further investigations in this direction could explore the feasibility of large-scale production and assess the environmental impact of utilizing Marang fruit wastes as a renewable energy source. Additionally, Marang fruit wastes hold tremendous potential for food and pharmaceutical applications. As evidenced by their rich bioactive compound content, Marang fruit by-products can be harnessed for the development of functional food products with health-promoting properties. Their phenolic and flavonoid compounds, known for their antioxidant and antimicrobial properties, make them promising candidates for the formulation of nutraceuticals and pharmaceutical products. Further research in this area could explore novel extraction methods to optimize bioactive compound yields and investigate potential bioactivities that could lead to new product developments in the food and pharmaceutical industries. Also, the potential of Marang seeds for various value-added products such as coffee, butter, starch, and other potential food products is not well exploited, and no established procedure has been disclosed.

Agricultural wastes have become an attractive source of nanocellulose not because of their large volume, but

due to their abundant organic in nature that comprises about 40%–50% cellulose and 20%–30% hemicellulose, with lesser amounts of lignin and other compounds such as sugars, oils, and minerals (Mateo et al., 2021; Seddiqi et al., 2021). The husk and peel of the fruit are rich in cellulose, making them attractive candidates for the production of cellulose-based materials (Padhi et al., 2023). Nanocellulose, a nanomaterial derived from cellulose, has gained significant attention due to its exceptional mechanical and chemical properties. This provides opportunities for researchers in the future to explore the potential of Marang fruit wastes as a main raw material for the extraction of cellulose and cellulose nanoparticles. Exploring innovative extraction and processing techniques for nanocellulose from Marang fruit wastes could unlock new possibilities for advanced materials and technologies.

Despite the substantial potential of Marang fruit wastes, several challenges must be addressed to facilitate their effective utilization. One significant concern is the fruit's seasonal nature, leading to limited availability throughout the year, which presents obstacles to continuous processing and supply. Moreover, Marang's territorial distribution, predominantly confined to specific regions in Southeast Asia, particularly remote areas, restricts accessibility and hinders large-scale utilization. Additionally, the handling and processing of Marang fruit can be labor-intensive and time-consuming, necessitating further research and optimization of extraction and purification methods for bioactive compounds. Addressing these challenges requires collaborative efforts among researchers, industries, and policymakers to unlock the full value of Marang fruit waste as a sustainable resource for diverse applications in food, pharmaceuticals, and other industries.

5 | CONCLUSIONS

In conclusion, the utilization of Marang fruit waste has shown great promise as a sustainable source for various valuable products. The identified products derived from these wastes include seed flour, biosorbents or adsorbents, and a diverse range of bioactive compounds with potential applications in the food and pharmaceutical industries. Among these, the production of biosorbents/adsorbents has received significant attention in current research. However, further investigations are needed to explore the full potential of Marang fruit wastes in food and pharmaceutical applications, as well as their potential as a source of cellulose and nanocellulose for various applications. Nonetheless, challenges related to seasonal availability and territorial distribution necessitate careful consideration in planning and implementing sustainable utilization strategies. Collaboration between researchers, industries, and policymakers is crucial to unlock the full value of Marang fruit waste and pave the way for a greener and more resource-efficient future.

AUTHOR CONTRIBUTIONS

Marjun C. Alvarado the sole author of this manuscript, has undertaken all essential steps in its completion, including conceptualization, data collection, analysis, and writing.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article.

ETHICS STATEMENT

None declared.

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