Journal of Advanced Research 20 (2019) 61–70

Contents lists available at ScienceDirect

Journal of Advanced Research

journal homepage: www.elsevier.com/locate/jare

Valorization of mangosteen, “The Queen of Fruits,” and new advances in postharvest and in food and engineering applications: A review

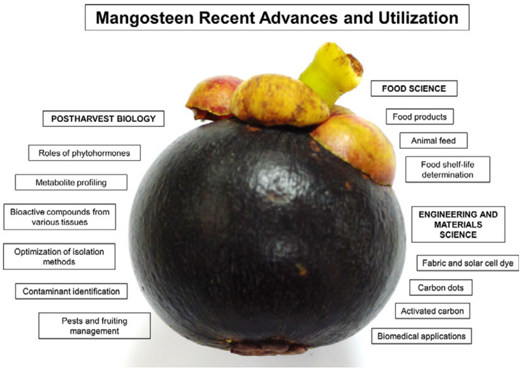
Wan Mohd Aizat [a,*], Faridda Hannim Ahmad-Hashim [a], Sharifah Nabihah Syed Jaafar [b]

[a] *Institute of Systems Biology (INBIOSIS), Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia*
[b] *Bioresource and Biorefinery Laboratory, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia*

HIGHLIGHTS

- This review highlights recent advances of mangosteen research in the postharvest, food and engineering fields.
- In postharvest fields, phytohormones, metabolites, and pest/disease management are described.
- Mangosteen has also been used in various food products and for animal feed supplementation.
- In engineering, mangosteen extract is useful in solar cells, carbon dots and advanced materials.
- Mangosteen-based products may benefit consumers and the engineering and biomedical industries.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 February 2019
Revised 24 May 2019
Accepted 24 May 2019
Available online 29 May 2019

Keywords:
Anthocyanin
Bioactivity
Flavonoid
Manggis
Mangostin
Xanthone

ABSTRACT

One of the most prolific plants utilized in various applications is mangosteen (*Garcinia mangostana* L.). Rich in potent bioactive compounds, such as xanthones, mangosteen is known to possess pharmacologically important anti-inflammatory and anti-tumor properties. However, most previous reviews have only discussed the application of mangosteen in medicinal areas, yet more recent studies have diverged and valorized its usage in other scientific fields. In this review, the utilization of this exotic fruit in postharvest biology (phytohormone roles, metabolite profiling, bioactive compounds, isolation method optimization, chemical contaminant identification, and management of pests and fruit disorders), food science (food products, animal feed supplementation, and food shelf-life determination), and engineering fields (fabric and solar cell dyes, carbon dots, activated carbon, and biomedical advanced materials) is presented in detail. Research papers published from 2016 onward were selected and reviewed to show the recent research trends in these areas. In conclusion, mangosteen has been utilized for various purposes, ranging from usage in industrially important products to applications in advanced technologies and biomedical innovation.

Introduction

Mangosteen (*Garcinia mangostana* L.) is an endemic evergreen tree species grown in tropical countries, such as Malaysia, Thailand, and Indonesia [1,2]. Mangosteen belongs to the

---

Peer review under responsibility of Cairo University.
* Corresponding author.
E-mail address: wma@ukm.edu.my (W.M. Aizat).

https://doi.org/10.1016/j.jare.2019.05.005
2090-1232/

Clusiaceae (Guttiferae) family [3,4] and is widely cultivated for its fruit, which is commonly termed the “Queen of Fruits” because of its unique sweet–sour taste [1,5]. Harvest of this fruit results in a major economic impact with nearly 700,000 tons produced worldwide in 2017 [6]. The fruit contains bioactive compounds, such as xanthones (Fig. 1a–g) and anthocyanins (Fig. 1h–i), which are mainly extracted from the fruit pericarp. Additionally, it possesses high antioxidant and anti-inflammatory properties. Mangosteen has been used to treat various diseases, including tumors, diabetes, bacterial infections, hypertension, and arthritis [1,7]. These applications suggest the usefulness of the fruit extract in medicinal and pharmaceutical contexts.

Xanthones are the main metabolites that contribute to the pharmaceutical applications of mangosteen extract. At least 70 xanthones have been characterized to date [1,8]. The xanthone structure is mainly composed of three consecutive aromatic rings differentiated by side chains (Fig. 1a). Interestingly, modifying these side chains is known to influence xanthone bioactivity [9,10]. Some of the major xanthones isolated from mangosteen fruit are α-mangostin (Fig. 1b), β-mangostin (Fig. 1c), γ-mangostin (Fig. 1d), gartanin (Fig. 1e), 8-deoxygartanin (Fig. 1f), and garcinone E (Fig. 1g). Other compounds, including anthocyanins, such as cyanidin-3-sophoroside (Fig. 1h) and cyanidin-3-glucoside (Fig. 1i) can also be abundantly found in the fruit pericarp [1].

Previously, several reviews have comprehensively addressed the fruit’s medicinal properties [1,8,11], such as anticarcinogenic [12–16], antibiofilm [17], antioxidant [18], antiperiodontitic [19], and antidiabetic [20] properties. Additionally, properties such as amelioration of metabolic disorders [7] and regulation of melanogenesis [21] have also been reported. Furthermore, other reviews have discussed the fruit extract’s potential in waste utilization [22] as well as from the perspective of somatic embryogenesis [23]. However, no critical evaluation of the various properties and utilization of the fruit in other scientific fields, such as postharvest biology, food science, and engineering and materials science, has been conducted.

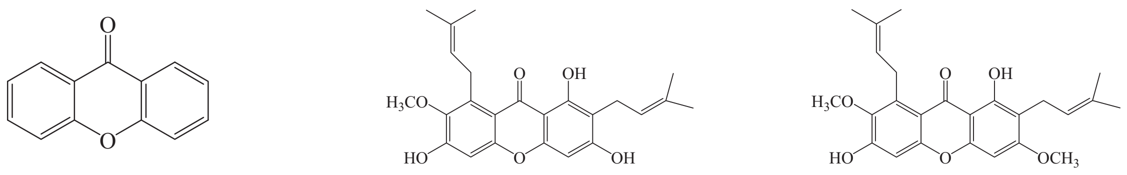
In this review, the properties and applicability of mangosteen in various fields are presented in detail (Fig. 2). Only publications from 2016 onward were considered using the keywords of “mangosteen AND *Garcinia mangostana*” searched in the Web of Science, PubMed, Scopus, EBSCO and Google Scholar databases. Furthermore, only full-text publications were considered, any short proceedings and transactions were excluded from this review, to be selective and nonredundant in the analysis.

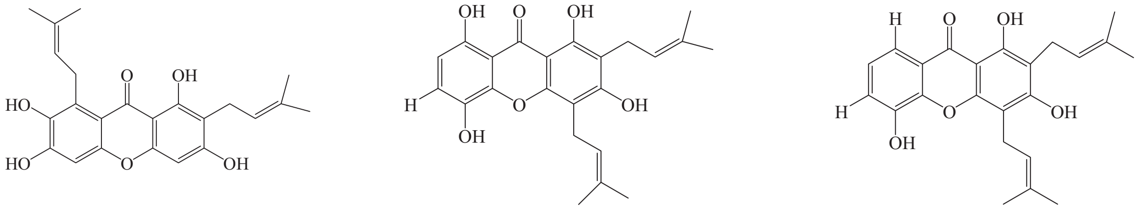
Postharvest biology

Mangosteen has been investigated in various aspects of postharvest biology, including determining the phytohormone roles in increasing fruit shelf life, metabolite profiling, identifying bioactive compounds from different tissues, identifying contaminants from the fruit and related products, and managing pests and diseases.

Roles of phytohormones

Mangosteen is known to be a climacteric fruit that relies on hormones, such as ethylene, to ripen. Various recent studies have investigated strategies to increase the shelf life of mangosteen. For example, Vo et al. [24] showed that storing mangosteen fruit at stage 3 (full red fruit) in a low-density polyethylene bag with a 1-methylcyclopropene sachet (ethylene perception inhibitor)


(a) Xanthone (b) α-Mangostin (c) β-Mangostin


(d) γ-Mangostin (e) Gartanin (f) 8-Deoxygartanin

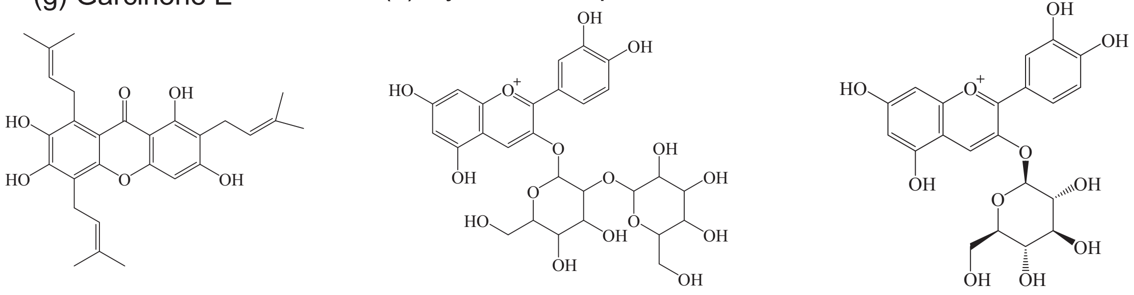

(g) Garcinone E (h) Cyanidin-3-sophoroside (i) Cyanidin-3-glucoside

Fig. 1. Various xanthones (a-g) and anthocyanins (h-i) isolated from mangosteen.

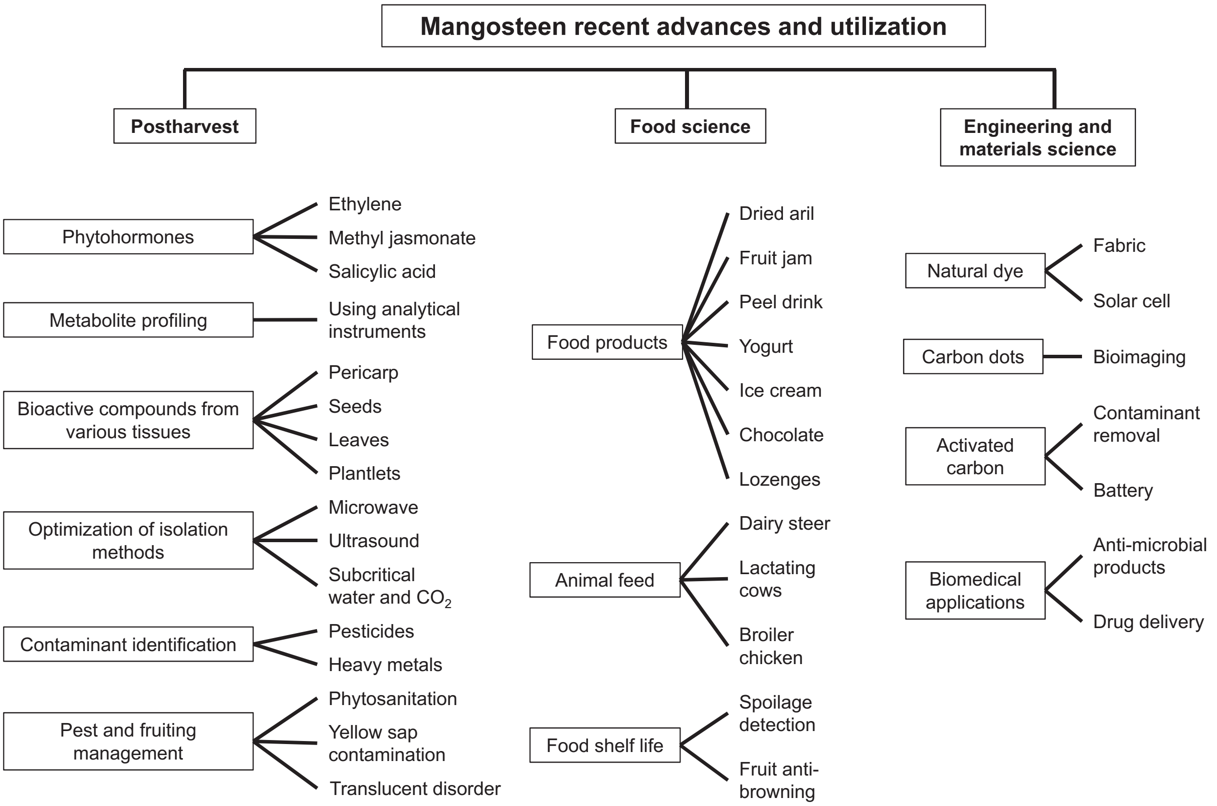


Fig. 2. Summary of recent advances and utilization of mangosteen in the fields of postharvest biology, food science, and engineering and materials sciences.

can prolong the ripening period and inhibit the development of fruit rot disease, thereby increasing the fruit shelf life. Another postharvest study by Mustafa et al. [25] described the use of two stress phytohormones methyl jasmonate (MeJA) and salicylic acid (SA), in delaying mangosteen pericarp hardening. The hardening of the fruit shell is often attributed to the lignification of the tissues as a response to injury. Applying MeJA and SA reduced the fruit hardness up to 12 days after harvest, suggesting the applicability of these hormones in fruit preservation [25]. Additionally, a microperforated polypropylene film bag containing holes for aeration was shown to be effective in maintaining mangosteen fruit quality over a 25-day storage period [26]. This finding suggests that controlling phytohormones released by the fruit is critical in postharvest mangosteen preservation.

Metabolite profiling

The postharvest characteristics of mangosteen ripening have been investigated in different fruit tissues using various analytical techniques, including gas chromatography-mass spectrometry. Metabolites related to the cell wall, such as galacturonic acid and xylose, increased during the ripening process, implying an active cell wall breakdown [27]. Psicose was also identified in the pericarp tissue, and the metabolite was suggested to play a role in protecting the fruit from excessive dehydration [27]. Other metabolites, including sugars (fructose and glucose) and amino acids (tryptophan, valine, phenylalanine, isoleucine, tyrosine, and serine), also increased during ripening in various mangosteen tissues (either pericarp, aril, or seeds), suggesting concerted metabolic activities during the process [27]. Other reports have also demonstrated that carbohydrates and simple sugars were abundantly present in the fruit pericarp [28,29].

Other metabolomic techniques, such as liquid chromatography-mass spectrometry and high-performance liquid chromatography (HPLC), have been used to further identify the compounds present in mangosteen fruit. For instance, using a high-accuracy liquid chromatography- quadrupole time-of-flight mass spectrometry system, Qin et al. [30] found that the composition of procyanidins in mangosteen consists of 47.7% monomers, 24.1% dimers, and 26.0% trimers, which may contribute to the high antioxidant activity of the fruit pericarp. Moreover, the levels of xanthone compounds in fruits harvested from various locations may vary. Using HPLC analysis, Muchtaridi et al. [31]; Muchtaridi et al. [32]; and Muchtaridi et al. [15] found that the levels of α-mangostin, γ-mangostin, and gartanin in the fruit pericarp differed among the fruits harvested from four different Indonesian districts. This result is interesting as fruits from different origins may show different metabolic profiles. Furthermore, using a new technique termed droplet-liquid microjunction-surface sampling probing, several xanthones, such as α-mangostin, β-mangostin, γ-mangostin, and gartanin, were identified from the dried fruit and leaf of mangosteen deposited in a herbarium [33]. Such a technique utilizes ultra-performance liquid chromatography coupled with a high-resolution mass spectrometry (Thermo Scientific^{TM} Q Exactive^{TM} Plus) for molecular mass determination and is able to preserve the sample integrity after the analysis [33].

Bioactive compounds from various tissues

Various mangosteen tissues, including pericarp, seeds, leaves, and plantlets, are known to contain bioactive compounds, such as phenolics and flavonoids. For instance, the *G. mangostana* pericarp showed significantly higher ($P < 0.05$) total phenolic, flavonoid, and anthocyanin content than that of other colored plant samples, such as *Syzygium cumini* (Java plum) fruit, *Clitoria ternatea* (butterfly pea) flower, and *Ardisia colorata* var. *elliptica* (chicken's eye) fruit [34]. The antioxidant capacity of mangosteen peel extract was the highest among that of other studied samples. This result may be attributed to the high concentration of various flavonoid and phenolic compounds, such as gallic acid, protocatechuic acid, chlorogenic acid, quercetin, epicatechin, rutin, catechin, and cyanidin-3-sophoroside [34].

Mangosteen seeds contain an increasing level of flavonoids and xanthones during development and germination phases, perhaps as a defensive strategy during these processes to protect seed viability [35,36]. In callus originated from young mangosteen leaves, several secondary metabolites, such as thiacremonone (a sulfur compound) and 7-methylthioheptanaldoxime (glucosinolate), were putatively identified upon elicitation using MeJA, a stress response hormone [37]. Moreover, under water deficit stress, mangosteen plantlets showed modulated secondary metabolite levels, including those of fatty acids (propyl oleate and hexadecenoic acid) and a terpenoid (neophytadiene), perhaps as a defense mechanism during drought stress [38]. This finding suggests that various tissues from mangosteen produce bioactive compounds, particularly in response to stress.

Optimization of isolation methods

Polyphenolic compounds, such as xanthones and flavonoids, are often most soluble in organic solvents and require nonpolar solvents for extraction and dissolution. Ghasemzadeh et al. [39] utilized an optimized microwave-assisted protocol for α-mangostin extraction using ethyl acetate as a solvent. They found high levels of extracted α-mangostin with high antioxidant and antibacterial properties. Similarly, the microwave-assisted approach and ultrasound technique have been optimized to extract flavonoids and anthocyanins from mangosteen, respectively [40,41]. Furthermore, Saputri [42] optimized a solid phase extraction (SPE) technique for α-mangostin extraction using ethanol as an eluent for an SPE cartridge octadecylsilane-5 filter. In addition, several xanthones, such as α-mangostin, β-mangostin, gartanin, 3-isomangostin, garcinone E, mangostanol, 8-desoxygartanin, and 9-hydroxycalabaxanthone, were extracted from mangosteen pericarp tissue using liquified dimethyl ether extraction [43]. However, most semipolar or nonpolar solvents such as acetone and dichloromethane, which are commonly used to extract mangosteen [44], are hazardous substances for human consumption and topical application. Therefore, the use of water-based extraction is desirable for wider biocompatibility. One unique property of water is that it can be boiled past its boiling temperature but retain its liquid form under a high-pressure condition, a state termed as subcritical water. This process allows nonpolar compounds to be dissolved, and this also has been performed for mangosteen xanthone extraction [45].

Another research study completed by Tan et al. [46] and Ng et al. [47] showed that a mild thermo-induced aqueous micellar biphasic system can be used to recover α- and γ-mangostin from mangosteen peel. This technique allows effective xanthone extraction without employing large volume of chemicals and sophisticated instruments, as is commonly used in chromatographic solvent extraction and supercritical fluid extraction, respectively [46,47]. This technique offers a quicker alternative to isolate valuable xanthones from the fruit and is a much greener approach. Furthermore, total phenolic content can be effectively extracted from mangosteen pericarp using supercritical carbon dioxide (CO_2) combined with hydrothermal extraction, as shown by Chhouk et al. [48].

Identification of chemical contaminants

Mangosteen postharvest research also focuses on contaminant identification. Phopin et al. [49] discovered that mangosteen fruit harvested from various farms in Thailand contained various pesticides, of which carbofuran, chlorothalonil, dimethoate, and metalaxyl exceeded the recommended maximum residue limit. However, these chemicals can be removed with running water (10 min soaking in water followed by gentle rubbing), and they were not present at a high concentration within the aril of the fruit [49], making the fruit safe for consumption. Siriangkhawut et al. [50] showed that mangosteen peel powder did not contain any heavy metals, including Cd and Pb, using ultrasound-assisted digestion coupled with flame atomic absorption spectrometry. Such analysis is important, as several other herbal products contain these heavy metals, which may affect consumers' health [50]. However, one unnamed herbal product based on mangosteen was found to exceed the limit of allowable Cd content (0.42 mg/kg) in the Philippines, suggesting that a thorough examination of such a product is imperative before human consumption [51].

Management of pests and fruit disorders

The management of pests and fruiting/flowering period are important aspects of mangosteen fruit industry. Insects, such as mealybugs (*Exallomochlus hispidus*), are a major threat to mangosteen production and export. This insect excretes sweet exudates on the fruit surface, promoting mold growth while reducing fruit quality [52,53]. This insect has caused great losses in the mangosteen industry, and as such, Indarwatmi et al. [54] developed a phytosanitary technique using ^{60}Co gamma irradiation at 250 Gy to inhibit the reproduction of the bugs while maintaining fruit quality. Another study by Tavera et al. [55] showed that, upon elicitation with *Aspidiotus rigidus*, a scale insect, mangosteen leaves emitted a high level of a particular terpene, kaur-16-ene. This volatile compound is a precursor to the phytohormone gibberellin. This finding indicated that when stressed, mangosteen tissues enhance growth-related processes to potentially compensate for the damage caused by such insects [55]. In another study, Ounlert et al. [56] built a mathematical model to predict the mangosteen flowering date by incorporating various factors, such as dry and rainy days, humidity, and temperature, in Thailand. Such a model is useful for the effective management of mangosteen orchards, particularly when deciding upon the optimal pesticide use and harvesting resources.

The two main problems for mangosteen growers and exporters are yellow sap contamination and translucent flesh disorder. The former is an abundance of yellow sap within the fruit pericarp and aril, reducing its appeal and leading to a bitter taste [57,58]. A recent study showed that this issue can be overcome by supplementing mangosteen trees with sufficient Ca nutrients and ensuring adequate sunlight during the fruiting period [57,58]. Translucent flesh disorder is characterized by translucent aril with crispy texture [59]. This disorder is a result of lignification upon hypoxic condition resulting from capillary water [59]. This disorder affects more fruit during the rainy season, particularly if it coincides with fruit developmental phase. Nakawajana et al. [60] developed a system based on electrical impedance spectroscopy to detect mangosteen fruit with translucent flesh disorder. This exemplifies that new advancements in technology are beneficial in characterizing postharvest symptoms.

Food science

Mangosteen research can also be found in food science. A number of reported studies have investigated its usage in food and functional food products, animal feed supplementation, and determination of food shelf life (Fig. 2).

Food and functional food products

Mangosteen fruit's unique sweet-sour taste has resulted in various usages in food products (Fig. 2). For instance, various humectants, such as maltitol, glycerol, and maltodextrin, have been investigated for optimal water content for mangosteen aril preservation [61]. The last compound (maltodextrin) showed better textural integrity and quality of the dried aril than other tested humectants [61]. Furthermore, the addition of mangosteen rind juice as a natural colorant into a sugar palm fruit jam named "Kolang-kaling" improved its red color, texture, and flavor, as preferred by trained panelists [62]. The jam-mangosteen mixture also had high moisture content, water activity, total dissolved solids, and crude fiber, suggesting that the fruit juice addition enhanced various organoleptic and chemical characteristics of the jam [62]. Interestingly, the color of the mangosteen-added jam may be due to anthocyanins other than malvidin 3,5-diglucoside chloride, cyanidin 3-O-glucoside chloride, and pelargonidin 3-glucoside chloride, as these anthocyanins were not detected in the HPLC analysis performed by Yenrina et al. [63]. Nonetheless, a mangosteen peel extract drink contained higher anthocyanin and antioxidant levels when added to 1% gelatin [64]. This result suggests that mangosteen extract added to gelatin can serve as a valuable functional drink. Furthermore, volatiles, such as (*E*)-2-hexenal, (*Z*)-3-hexen-1-ol, hexan-1-ol, and hexanal, were found to be the main contributors to the mangosteen fruit juice's distinctive smell [65]. This smell will also determine consumers' perception and acceptance of the product.

Other functional foods that have been fortified with mangosteen fruit extract are yogurt, ice cream, chocolate, and lozenges. A study performed by Shori et al. [66] indicated that the addition of mangosteen pulp and pericarp extracts into the Phytomix-3 mixture (containing a mixture of *Lycium barbarum*, *Momordica grosvenori*, and *Psidium guajava* leaves) increased the total phenolic compounds ($P < 0.05$) of the resulting yogurt. Consequently, this increased the antioxidant activity of the yogurt by approximately 37–43% during 14 days of storage. A sensory evaluation test by consumers also showed high preference (particularly in regard to sweetness and aroma) toward the yogurt with the added mangosteen extract [66]. This observation suggests that the addition of mangosteen mix increases not only the levels of some chemical constituents in the yogurt but also its appeal to consumers. In addition, Hiranrangsee et al. [41] used mangosteen fruit puree and extracted anthocyanin to supplement ice cream. The study further showed that the anthocyanin content (up to 2% w/w) increased the antioxidant level of the ice cream. Furthermore, mangosteen pericarp extract has been used in chocolate production [67] and lozenges [68], suggesting the applicability of mangosteen extract in various types of food fortification.

Animal feed supplementation

Mangosteen has also been used as animal feed. For example, mangosteen peel powder has been used as feed supplementation for dairy steer and lactating cows without an adverse impact on the livestock's diets [69,70]. Such supplementation improved various aspects of the steers' digestion, microbiome composition, and rumen fermentation [69,70]. Furthermore, Hidanah et al. [71] reported that mangosteen peel addition into broiler chicken feed can increase the chickens' weight during heat stress. Such observations may be attributed to the bioactive components of mangosteen peel, such as xanthones, that may improve chicken tolerance during stress [71]. Furthermore, mangosteen waste branches have been converted to pyroligneous acid via carbonization [72]. This compound exhibits high phenolic and antioxidant levels and can be used as an animal feed supplement [72]. However, further investigation, particularly at the molecular level, should be performed to investigate the regulatory role played by mangosteen compounds in promoting the general health of poultry and livestock.

Measuring and prolonging food shelf life

Mangosteen compound has been used in measuring and prolonging food shelf life. For instance, a biofilm coated with anthocyanin extract from mangosteen was also able to detect spoilage of chicken nuggets via color indication [73]. Meanwhile, cyanidin-3-sophoroside, a major anthocyanin from the fruit rind, has been shown to act as an anti-browning agent for apple cuts [74]. The compound action was elucidated as a potent allosteric inhibitor of polyphenol oxidase, an enzyme responsible for melanin (brown pigment) generation [74]. Undeniably, this finding further expands the use of mangosteen in various food industries and applications.

Engineering and material sciences

Mangosteen has several applications in the field of engineering and materials science. For instance, different parts of the plants have been exploited and converted into valuable components of fabric and solar cells, carbon dots (C-dots), activated carbons (ACs), and biomedical advanced materials (Fig. 2).

Natural dye for fabric and solar cells

One of the most native uses of mangosteen in this field is perhaps as a natural dye due to its prominent color. Fully ripened mangosteen pericarp contains anthocyanins, such as cyanidin-3-sophoroside and cyanidin-3-glucoside (Fig. 1h-i), which contribute to the dark purple/red color of its pericarp [75–77]. Other compounds, such as tannin, can also be extracted from mangosteen for another (brown) coloring property [78]. The use of these natural dyes in the textile industry shows great potential, as they can be inexpensively obtained (such as from the fruit pericarp waste) and are safe for the environment (biodegradable and nontoxic) compared with synthetic dyes, such as Ru complexes. For instance, Kusumawati et al. [78] successfully dyed cotton fabrics using mangosteen extract. Interestingly, the use of fixing chemicals, such as iron sulfate, alum, and lime, along with the extract generated different fabric colors, namely, green, light brown, and dark brown, respectively. Meanwhile, Faiz et al. [79] showed that vitamin C treatment improves the color retention of silk fabric dyed with mangosteen husk. These studies exemplify that mangosteen waste extract can be applied to the fabric industry as an inexpensive natural dye.

Mangosteen dark purple dye is also valuable for creating dye-sensitized solar cells (DSSCs). A DSSC is composed of a nanocrystalline porous semiconductor electrode, an auxiliary electrode, and an electrolyte. A DSSC is considered a third-generation solar cell, particularly used for light energy harvesting to generate electricity (Fig. 3). Among the main processes in DSSC operation is absorption that regulates cell efficiency. Such a process requires the use of potent dyes coated on the surface of the electrode to absorb considerable light energy. Natural dyes are preferred for DSSC fabrication due to their low cost and easy fabrication and purification [80].

Evidently, fabricated DSSCs using crude mangosteen extract showed a maximum light to-current conversion efficiency (η) of 0.97% [81]. The natural dyes that contain anthocyanin have the highest η as they can efficiently assist the electron mobility of the metal oxide semiconductor. This function is due to the existing active carbonyl ($-C{=}O$) and hydroxyl ($-OH$) groups in the anthocyanin structure. Tontapha et al. [80] successfully fabricated a DSSC using α-mangostin and anthocyanin extracted with different solvents, such as acidified acetone and ethanol. Another study using a lithium bis(oxalato)borate-based electrolyte showed that

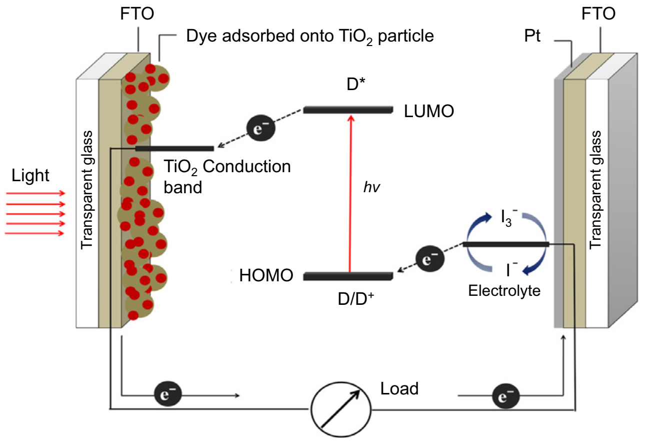


Fig. 3. Mangosteen dye can be coated onto a titanium dioxide (TiO_2) surface to absorb light that passes through transparent glass to generate electricity [80]. FTO, fluorine-doped tin oxide; HOMO, highest occupied molecular orbital energy; LUMO, lowest unoccupied molecular orbital energy; Pt, platinum. Copyright Springer Nature reprinted with permission.

the efficiency of a DSSC sensitized with mangosteen dye extract was higher than those sensitized with other natural dyes, such as extracts of blueberry, spinach, and red cabbage [82]. Furthermore, DSSCs fabricated using biocapped zinc oxide nanoparticles and mangosteen dye as sensitizers resulted in a high cell efficiency [83]. These lines of evidence suggest that mangosteen extract has been fabricated in various manners to generate a highly efficient DSSC, which can potentially be used in future solar cells.

C-dots for bioimaging

Another emerging field for mangosteen application is the generation of C-dots for biosensory analysis. C-dots are a new class of carbon nanospheres that are smaller than 10 nm in size and have fascinating luminescent properties, high stability, and chemical inertness [84]. Furthermore, C-dots possess super solubility in water, biocompatibility, optical properties, and low cytotoxicity [84]. Currently, C-dots are being used in various applications, such as optoelectronic devices, photocatalysts, electrocatalysts, and bioimaging [84]. C-dots can be synthesized from natural carbon sources, including mangosteen fruit.

In a recent study, mangosteen pulp was successfully synthesized into C-dots using a simple calcined method, eliminating the need for harmful chemicals [85]. Mangosteen C-dots showed excellent potential in analyzing Fe^{3+} ions within a linear range from 0 to 0.18 mM. This excellent potential is due to the presence of carboxyl and hydroxyl groups on the C-dot surface that form a high-affinity binding and rapid chelation with Fe^{3+}. Furthermore, the synthesized C-dots show an outstanding fluorescent temperature probe toward reversible and restorable properties during temperature change. These fluorescent C-dots can be preferentially used for bioimaging as shown by their biocompatibility with yeast cells [85] (Fig. 4).

Another important C-dot study using pyrolyzed mangosteen peel was conducted by Aji et al. [86]. This method used urea as a passivation agent to catalyze C-dot formation from the carbon source (mangosteen water extract). Other than the urea concentration, the reaction temperature can also influence the photoluminescent properties of C-dots. Interestingly, a higher incubation temperature (up to 300 °C) resulted in smaller C-dots and increased luminescence, a phenomenon that may be attributed to the C—N bond trapping emission energy.

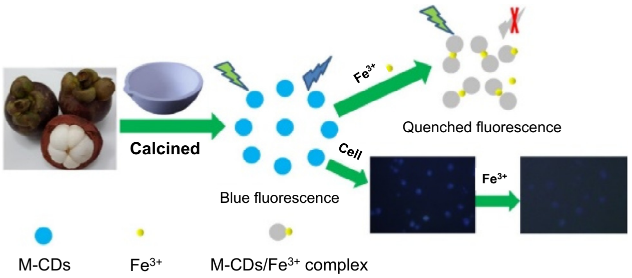


Fig. 4. Synthesis of mangosteen carbon dots (M-CDs) from the fruit and their potential use for Fe^{3+} chelation and cell imaging [85]. Copyright Elsevier reprinted with permission.

AC for contaminant removal and battery components

Mangosteen pericarp can serve as an appropriate source for AC production because its tissue consists of low ash and high carbon content originating from structural cellulose, lignin, and hemicellulose. The process to produce AC involves tissue grinding into small materials (approximately less than 80 mesh) before drying at approximately 65 °C. AC is a good adsorbent, as it has a high surface area. AC usage is perhaps among the easiest and cheapest water purification strategies compared with other conventional techniques, such as chemical oxidation, biological treatment, and membrane filtration [87].

Carbonized mangosteen tissues have been used for contaminant removal. For instance, the use of a mangosteen shell as AC functionalized by nitrogen-doped titanium dioxide (N-TiO_2) was able to effectively remove (up to 80%) the pollutant Remazol Brilliant Blue (RBB) in the presence of solar energy (Fig. 5) [88]. RBB is known as a toxic chemical dye from the fabric industry, and hence, the fabricated photocatalyst N-TiO_2 can be used for treating and removing such waste [88]. Mangosteen peel synthesized into magnetic biochar using the pyrolysis technique can remove methylene blue, cadmium ion [89], plumbum ion, rhodamine B dye [90], and lead [91] contaminants from wastewater. Similarly, AC derived from mangosteen peel has been embedded into calcium-alginate beads to remove aqueous methylene blue [92,93]. Another study using mangosteen peel AC was able to adsorb and remove CO_2 [94], suggesting its potential application for CO_2 removal from combustion. Furthermore, mangosteen pericarp powder has been used as a coagulant, effectively removing up to 99% of water turbidity in the presence of aluminum sulfate [95]. This property may be attributed to the mangosteen powder microcoil structure, which entraps contaminants and impurities in the water [95]. Interestingly, AC from a mangosteen shell prepared by potassium hydroxide activation was able to purify and refine biodiesel from impurities [96], suggesting its wide applications.

AC generated from mangosteen rind is also utilized in battery production. A hierarchical porous carbon generated from carbonized and activated mangosteen rind was able to deliver a high discharge capacity of up to 870 mAh/g when used as a composite cathode for a lithium sulfur battery [97]. Furthermore, the cell demonstrated a high capacity retention and capability rate [97,98]. In addition, a low-cost hard carbon (HC) anode for sodium ion batteries was developed from the mangosteen peel by Wang et al. [99]. The fabricated HC showed a low average potential but high reversible capacity. The maximum specific capacity achieved by the HC sample was 330 mAh/g after 100 cycles with excellent capacity retention (98%). In the future, these fabricated batteries from such biomass waste may be able to replace rechargeable lithium-ion batteries in portable electronics and energy storage systems.

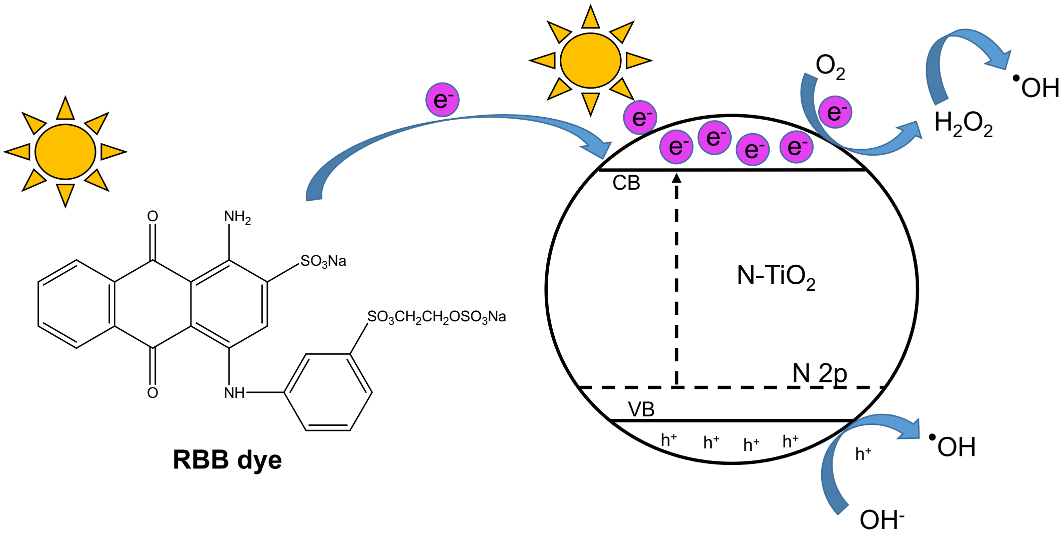


Fig. 5. Mechanism of Remazol Brilliant Blue (RBB) reaction with a nitrogen-doped titanium dioxide (N-TiO_2) developed from a mangosteen shell in the presence of solar light energy [88]. Open access article with no copyright permission.

Biomedical advanced materials

The medicinal properties of mangosteen extract have sparked interest in their utilization in advanced materials of biomedical benefit. For instance, rubber latex gloves embedded with powder from mangosteen peel extract have an antimicrobial property for use in a medical environment [100]. Furthermore, an electrospun polyacrylonitrile fiber mixed with dried mangosteen water extract possesses anti-microbial activities against various *Staphylococcus* and *Mycobacterium tuberculosis* strains [101]. Such a fiber is therefore useful in minimizing bacterial contamination, particularly preventing the spread of tuberculosis for many filtration applications, including facemasks and respirators. Electrospun nanofibers developed from polyvinylpyrrolidone with encapsulated mangosteen extract exhibited high antioxidant activity [102,103]. The nanofiber allows mangosteen extract/compounds to disperse throughout the fiber's molecular structure, increasing the surface area for efficient drug delivery application [102,103].

Furthermore, microemulsion of α-mangostin may have potential for drug delivery as the nanosized particles improve the compound bioavailability, and it was indeed highly present in treated rat organs, such as the stomach, liver, and spleen [104,105]. Similarly, mangosteen ethyl acetate fraction loaded into a self-nanoemulsifying drug delivery system was able to penetrate the skin layer (*stratum corneum*), suggesting its applicability for cosmetic products or skin damage treatment [106,107]. Mangosteen extract has also been applied as a topical gel. Priani et al. [108] developed a microemulsion gel containing an *n*-hexane fraction of mangosteen pericarp that is able to protect skin from UV exposure (a sun protection factor of 4.01). Furthermore, Astuti et al. [109] used gel formulation of mangosteen rind (ethyl acetate extract) mixed with sodium polyacryloydimethyl taurate (gelling agent), propylene glycol (humectant), glycerin (cosolvent), MicroCare® preservative, and an alkalizing agent for the controlled release of α-mangostin. This formulation is important for a skin application with a prolonged anti-bacterial property.

Another strategy to increase the solubility and, hence, the bioavailability of xanthones, particularly α-mangostin, has been reported by Phunpee et al. [110]. This study utilized quaternized beta-cyclodextrin grafted chitosan to generate an inclusion complex with α-mangostin. The results showed that the α-mangostin complex was gradually released within a simulated saliva buffer compared with the dissoluble free α-mangostin. Furthermore, anti-inflammatory and antimicrobial activities against *Streptococcus mutans* and *Candida albicans* were significantly higher for the α-mangostin inclusion complex compared with its free form, which is possibly attributed to the increased solubility of the complex [110]. Mangosteen has also been used as a modified carrier molecule. Nano-fibrillated cellulose developed from its rind was used to emulsify and encapsulate vitamin D to facilitate compound bioavailability within the gastrointestinal tract [111].

Another advanced material using mangosteen in the biomedical industry is metallic nanoparticles. For instance, gold nanoparticle (AuNP) has been promoted as a drug and antibody delivery system due to its multiple surface functionality [112]. Natural products, such as mangosteen peel, have been used as reducing agents to generate AuNP using a greener approach [112,113]. Moreover, the biofabrication of mangosteen bark extract with silver nanoparticle (AgNP), in combination with ultrasonic exposure, has enabled targeted cancer treatment [114,115]. This advancement is particularly important because, during a single ultrasonic treatment, healthy and cancerous cells are negatively impacted. The use of the AgNP successfully reduced the population of cancerous cells (lung cancer) by more than two fold but did not affect healthy normal cells [114]. Additionally, copper nanoparticle prepared with the addition of mangosteen leaf extract has shown promising antibacterial activities against *Escherichia coli* and *Staphylococcus aureus* [116]. These lines of evidence suggest that mangosteen biomass waste can be valorized into highly valuable components in the medicinal and pharmaceutical fields, benefitting societal well-being in the long term. As first coined by Fairchild [117], mangosteen is truly the "Queen of Fruits."

Conclusions and future perspectives

This review summarizes recent literature about mangosteen properties, uses, and applications in various industries and scientific fields. The fruit shelf life, ripening process, and metabolite composition were investigated in several postharvest studies. Furthermore, mangosteen has been used in the food industry, particularly as functional food, animal feed, and for food shelf-life determination. Other areas of interest are engineering and materials sciences. Mangosteen extract has been utilized in natural fabric dye, DSSCs, biosensory applications, contaminant removal, battery production, and antibacterial and anticancer materials. This wide utilization of mangosteen, ranging from technological and biomedical applications to advanced materials, deserves the utmost attention of local governments to further promote the fruit and its cultivation. In the future, mangosteen-derived products are envisioned to benefit various communities, including local growers, farmers, and consumers, as well as the biomaterial and biomedical industries.

Conflict of interest

The authors have declared no conflict of interest

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects

Acknowledgements

This research was supported by the UKM Research University grant (DIP-2018-001), Ministry of Education (MOE), Malaysia (FRGS/2/2014/SG05/UKM/02/2), and the Ministry of Science, Technology and Innovation (MOSTI), Malaysia (02-01-02-SF1237). We would like to thank Prof. Dr. Mukram Mohamed Mackeen from Universiti Kebangsaan Malaysia (UKM), Malaysia, and Prof. Dr. Sahidin Sutriadi from Universitas Halu Oleo, Indonesia, for providing valuable insights on improving the manuscript, particularly the phytochemistry portion.

References

[1] Aizat WM, Jamil IN, Ahmad-Hashim FH, Normah MN. Recent updates on metabolite composition and medicinal benefits of mangosteen plant. PeerJ 2019;7:e6324.

[2] Marzaimi IN, Aizat WM. Current review on mangosteen usages in antiinflammation and other related disorders. In: Watson RR, Preedy VR, editors. Bioactive food as dietary interventions for arthritis and related inflammatory diseases. United Kingdom: Academic Press; 2019. p. 273–89.

[3] Matra DD, Poerwanto R, Santosa E, Higashio H, Anzai H, Inoue E. Analysis of allelic diversity and genetic relationships among cultivated mangosteen (*Garcinia mangostana* L.) in Java, Indonesia using microsatellite markers and morphological characters. Trop Plant Biol 2016;9:29–41.

[4] Nazre M, Newman MF, Pennington RT, Middleton DJ. Taxonomic revision of *Garcinia* Section Garcinia (Clusiaceae). Phytotaxa 2018;373:1–52.

[5] Midin MR, Nordin MS, Madon M, Saleh MN, Goh H-H, Noor NM. Determination of the chromosome number and genome size of *Garcinia mangostana* L. via cytogenetics, flow cytometry and k-mer analyses. Caryologia 2018;71:35–44.

[6] Altendorf S. Minor tropical fruits: mainstreaming a niche market. Food and Agriculture Organization of the United Nations (www.fao.org); 2018. , http://www.fao.org/fileadmin/templates/est/COMM_MARKETS_MONITORING/Tropical_Fruits/Documents/Minor_Tropical_Fruits_FoodOutlook_1_2018.pdf.

[7] Tousian Shandiz H, Razavi BM, Hosseinzadeh H. Review of *Garcinia mangostana* and its xanthones in metabolic syndrome and related complications. Phytother Res 2017;31:1173–82.

[8] Ovalle-Magallanes B, Eugenio-Pérez D, Pedraza-Chaverri J. Medicinal properties of mangosteen (*Garcinia mangostana* L.): a comprehensive update. Food Chem Toxicol 2017;109:102–22.

[9] Buravlev EV, Shevchenko OG, Anisimov AA, Suponitsky KY. Novel Mannich bases of α-and γ-mangostins: synthesis and evaluation of antioxidant and membrane-protective activity. Eur J Med Chem 2018;152:10–20.

[10] Karunakaran T, Ee GCL, Ismail IS, Mohd Nor SM, Zamakshshari NH. Acetyl-and O-alkyl-derivatives of β-mangostin from *Garcinia mangostana* and their anti-inflammatory activities. Nat Prod Res 2018;32:1390–4.

[11] Wang MH, Zhang KJ, Gu QL, Bi XL, Wang JX. Pharmacology of mangostins and their derivatives: a comprehensive review. Chin J Nat Med 2017;15:81–93.

[12] Zhang K-J, Gu Q-L, Yang K, Ming X-J, Wang J-X. Anticarcinogenic effects of α-mangostin: a review. Planta Med 2017;83:188–202.

[13] Brito LdC, Berenger ALR, Figueiredo MR. An overview of anticancer activity of *Garcinia* and *Hypericum*. Food Chem Toxicol 2017;109:847–62.

[14] Moosavi MA, Haghi A, Rahmati M, Taniguchi H, Mocan A, Echeverría J, et al. Phytochemicals as potent modulators of autophagy for cancer therapy. Cancer Lett 2018;424:46–69.

[15] Muchtaridi M, Wijaya CA. Anticancer potential of α-mangostin. Asian J Pharm Clin Res 2017;10:440–5.

[16] Iqbal J, Abbasi BA, Batool R, Mahmood T, Ali B, Khalil AT, et al. Potential phytocompounds for developing breast cancer therapeutics: Nature's healing touch. Eur J Pharmacol 2018;827:125–48.

[17] Agarwal H, Gayathri M. Biological synthesis of nanoparticles from medicinal plants and its uses in inhibiting biofilm formation. Asian J Pharm Clin Res 2017;10:64–8.

[18] Ibrahim UK, Kamarrudin N, Suzihaque MUH, Hashib SA. Local fruit wastes as a potential source of natural antioxidant: an overview. IOP Conf Ser Mater Sci Eng 2017;206:012040.

[19] Milovanova-Palmer J, Pendry B. Is there a role for herbal medicine in the treatment and management of periodontal disease? J Herb Med 2018;12:33–48.

[20] Mohd Bukhari DA, Siddiqui MJ, Shamsudin SH, Rahman MM, So'ad SZM. Alpha-glucosidase inhibitory activity of selected Malaysian plants. J Pharm Bioallied Sci 2017;9:164–70.

[21] Pillaiyar T, Manickam M, Jung SH. Recent development of signaling pathways inhibitors of melanogenesis. Cell Signal 2017;40:99–115.

[22] Cheok CY, Mohd Adzahan N, Abdul Rahman R, Zainal Abedin NH, Hussain N, Sulaiman R, et al. Current trends of tropical fruit waste utilization. Crit Rev Food Sci Nutr 2018;58:335–61.

[23] Mahdavi-Darvari F, Noor NM, Ismanizan I. Epigenetic regulation and gene markers as signals of early somatic embryogenesis. Plant Cell Tissue Organ Cult 2015;120:407–22.

[24] Vo T, Jitareerat P, Uthairatanakij A, Limmatvapirat S, Kato M. Effect of low density polyethylene bag and 1-MCP sachet for suppressing fruit rot disease and maintaining storage quality of mangosteen (*Garcinia mangostana* L.). Int Food Res J 2016:23.

[25] Mustafa MA, Ali A, Seymour G, Tucker G. Delayed pericarp hardening of cold stored mangosteen (*Garcinia mangostana* L.) upon pre-treatment with the stress hormones methyl jasmonate and salicylic acid. Sci Hortic 2018;230:107–16.

[26] Van Phong N, Nhung DTC. Effects of microperforated polypropylene film packaging on mangosteen fruits quality at low temperature storage. J Exp Bio Agri Sci 2016;4:706–13.

[27] Parijadi AA, Putri SP, Ridwani S, Dwivany FM, Fukusaki E. Metabolic profiling of *Garcinia mangostana* (mangosteen) based on ripening stages. J Biosci Bioeng 2018;125:238–44.

[28] Mamat SF, Azizan KA, Baharum SN, Mohd Noor N, Aizat WM. Metabolomics analysis of mangosteen (*Garcinia mangostana* Linn.) fruit pericarp using different extraction methods and GC-MS. Plant Omics 2018;11:89.

[29] Ferey J, Da Silva D, Lafite P, Daniellou R, Maunit B. TLC-UV hyphenated with MALDI-TOFMS for the screening of invertase substrates in plant extracts. Talanta 2017;170:419–24.

[30] Qin Y, Sun Y, Li J, Xie R, Deng Z, Chen H, et al. Characterization and antioxidant activities of procyanidins from lotus seedpod, mangosteen pericarp, and camellia flower. Int J Food Prop 2017;20:1621–32.

[31] Muchtaridi M, Afiranti FS, Puspasari PW, Subarnas A, Susilawati Y. Cytotoxicity of *Garcinia mangostana* L. pericarp extract, fraction, and isolate on *HeLa* cervical cancer cells. Int J Pharm Sci Res 2018;10:348–51.

[32] Muchtaridi M, Puteri NA, Milanda T, Musfiroh I. Validation analysis methods of α-mangostin, ϒ-mangostin and gartanin mixture in mangosteen (*Garcinia mangostana* L.) fruit rind extract from west java with HPLC. J Appl Pharm Sci 2017;7:125–30.

[33] Kao D, Henkin JM, Soejarto DD, Kinghorn AD, Oberlies NH. Non-destructive chemical analysis of a *Garcinia mangostana* L. (mangosteen) herbarium voucher specimen. Phytochem Lett 2018;28:124–9.

[34] Azima AS, Noriham A, Manshoor N. Phenolics antioxidants and color properties of aqueous pigmented plant extracts: *Ardisia colorata* var. *elliptica*, *Clitoria ternatea*, *Garcinia mangostana* and *Syzygium cumini*. J Funct Foods 2017;38:232–41.

[35] Mazlan O, Aizat WM, Baharum SN, Azizan KA, Noor NM. Metabolomics analysis of developing *Garcinia mangostana* seed reveals modulated levels of sugars, organic acids and phenylpropanoid compounds. Sci Hortic 2018;233:323–30.

[36] Mazlan O, Aizat WM, Zuddin NSA, Baharum SN, Noor NM. Metabolite profiling of mangosteen seed germination highlights metabolic changes related to carbon utilization and seed protection. Sci Hortic 2019;243:226–34.

[37] Jamil SZMR, Rohani ER, Baharum SN, Noor NM. Metabolite profiles of callus and cell suspension cultures of mangosteen. 3. Biotech 2018;8:1–14.

[38] Hapsari DP, Poerwanto R, Sopandie D, Santosa E. Partial root-zone irrigation effects on growth, metabolism and calcium status of mangosteen seedling (*Garcinia mangostana* L.). Adv Hortic Sci 2018;32:49–59.

[39] Ghasemzadeh A, Jaafar H, Baghdadi A, Tayebi-Meigooni A. Alpha-mangostin-rich extracts from mangosteen pericarp: Optimization of green extraction protocol and evaluation of biological activity. Molecules 2018;23:1852.

[40] Hasan A, Nashrianto H, Juhaeni R. Artika I. Optimization of conditions for flavonoids extraction from mangosteen (Garcinia mangostana L.). Pharm Lett 2016;8:114–20.

[41] Hiranrangsee L, Kumaree KK, Sadiq MB, Anal AK. Extraction of anthocyanins from pericarp and lipids from seeds of mangosteen (*Garcinia mangostana* L.) by Ultrasound-assisted extraction (UAE) and evaluation of pericarp extract enriched functional ice-cream. J Food Sci Technol 2016;53:3806–13.

[42] Saputri FA. The optimization of eluting condition of solid phase extraction method for α-mangostin purification in mangosteen pericarp extract. Int J App Pharm 2017;10:112–4.

[43] Nerome H, Hoshino R, Ito S, Esaki R, Eto Y, Wakiyama S, et al. Functional ingredients extraction from *Garcinia mangostana* pericarp by liquefied dimethyl ether. Eng J 2016;20:155–62.

[44] Bundeesomchok K, Filly A, Rakotomanomana N, Panichayupakaranant P, Chemat F. Extraction of α-mangostin from *Garcinia mangostana* L. using alternative solvents: Computational predictive and experimental studies. LWT-Food Sci Technol 2016;65:297–303.

[45] Machmudah S, Lestari SD, Kanda H, Winardi S, Goto M. Subcritical water extraction enhancement by adding deep eutectic solvent for extracting xanthone from mangosteen pericarps. J Supercrit Fluids 2018;133:615–24.

[46] Tan GYT, Zimmermann W, Lee K-H, Lan JC-W, Yim HS, Ng HS. Recovery of mangostins from *Garcinia mangostana* peels with an aqueous micellar biphasic system. Food Bioprod Process 2017;102:233–40.

[47] Ng H-S, Tan GYT, Lee K-H, Zimmermann W, Yim HS, Lan JC-W. Direct recovery of mangostins from *Garcinia mangostana* pericarps using cellulase-assisted aqueous micellar biphasic system with recyclable surfactant. J Biosci Bioeng 2018;126:507–13.

[48] Chhouk K, Quitain AT, Pag-asa DG, Maridable JB, Sasaki M, Shimoyama Y, et al. Supercritical carbon dioxide-mediated hydrothermal extraction of bioactive compounds from *Garcinia mangostana* pericarp. J Supercrit Fluids 2016;110:167–75.

[49] Phopin K, Wanwimolruk S. Prachayasittikul V. Food safety in Thailand. 3: Pesticide residues detected in mangosteen (*Garcinia mangostana* L.), queen of fruits. J Sci Food Agric 2017;97:832–40.

[50] Siriangkhawut W, Sittichan P, Ponhong K, Chantiratikul P. Quality assessment of trace Cd and Pb contaminants in Thai herbal medicines using ultrasound-assisted digestion prior to flame atomic absorption spectrometry. J Food Drug Anal 2017;25:960–7.

[51] De Vera JS, Quirit LB, Rodriguez IB. Determination of Cr, Cd, Sn, and Pb in selected herbal products available in Philippine markets. Sci Diliman 2017;29:82–96.

[52] Indarwatmi M, Dadang D, Ridwani S, Sri Ratna E. The bionomics of the cocoa mealybug, *Exallomochlus hispidus* (Morrison) (Hemiptera: Pseudococcidae), on mangosteen fruit and three alternative hosts. Insects 2017;8:1–9.

[53] Kuswadi AN, Indarwatmi M, Nasution IA, Sasmita HI. Minimum gamma irradiation dose for phytosanitary treatment of *Exallomochlus hispidus* (Hemiptera: Pseudococcidae). Fla Entomol 2016;99:69–75.

[54] Indarwatmi M, Dadang Sobir, Ratna ES. Phytosanitary irradiation against cocoa mealybug *Exallomochlus hispidus* (Morrison) (Hemiptera: Pseudococcidae) on mangosteen fruits. J Entomol 2017;14:208–15.

[55] Tavera M, Lago J, Magalong V, Vidamo G, Carandang J, Amalin D, et al. Effect of *Aspidiotus rigidus* infestation on the volatile chemical profile of the host plant *Garcinia mangostana*. Hell Plant Prot J 2018;11:1–8.

[56] Ounlert P, Sdoodee S, Tongkhow P. The mangosteen flowering date model in Nakhon Si Thammarat Province, southern Thailand. J Cent Eur Agric 2017:18.

[57] Tanari Y, Efendi D, Poerwanto R, Sopandie D. Application of calcium to decrease yellow sap contamination at different positions of *Garcinia mangostana* L. Adv Hortic Sci 2018;32:169–75.

[58] Kurniadinata OF, Depari SO, Poerwanto R, Efendi D, Wachjar A. Solving yellow sap contamination problem in mangosteen (*Garcinia mangostana*) with Ca^{2+} application based on fruit growth stage. Commun Biom Crop Sci 2016;11:105–13.

[59] Noichinda S, Bodhipadma K, Kong-In S. Capillary water in pericarp enhances hypoxic condition during on-tree fruit maturation that induces lignification and triggers translucent flesh disorder in mangosteen (*Garcinia mangostana* L.). J Food Qual 2017:1–7.

[60] Nakawajana N, Terdwongworakul A, Teerachaichayut S. Minimally destructive assessment of mangosteen translucency based on electrical impedance measurements. J Food Eng 2016;171:137–44.

[61] Charoen R, Tipkanon S, Savedboworn W. Sorption isotherm study of preserved wild mangosteen (kra-thon yhee) with replacing humectants. Int Food Res J 2018:25.

[62] Sayuti K, Yenrina R, Anggraini T. Characteristics of "Kolang-kaling"(sugar palm fruit jam) with added natural colorants. Pak J Nutr 2017;16:69–76.

[63] Yenrina R, Sayuti K, Nakano K, Thammawong M, Anggraini T, Fahmy K, et al. Cyanidin, malvidin and pelargonidin content of "Kolang-Kaling" jams made with juices from asian melastome (*Melastoma malabathricum*) fruit, java plum (*Syzygium cumini*) fruit rind or mangosteen (*Garcinia mangostana*) fruit rind. Pak J Nutr 2017;16:850–6.

[64] Hanafi SMS, Irawan C, Rochaeni H. Effect gelatine of the characteristic functional drink from mangosteen peel extract (*Garcinia mangostana*). J Pharmacogn Phytochem 2017;6:332–5.

[65] Holm M, Chen D, Seow Y, Ong P, Liu S. Volatile flavour compounds of mangosteen juice and wine fermented with *Saccharomyces cerevisiae*. Int Food Res J 2016;23:1812–7.

[66] Shori AB, Rashid F, Baba AS. Effect of the addition of phytomix-3+ mangosteen on antioxidant activity, viability of lactic acid bacteria, type 2 diabetes key-enzymes, and sensory evaluation of yogurt. LWT-Food Sci Technol 2018;94:33–9.

[67] Sim SY, Ng JW, Ng WK, Forde CG, Henry CJ. Plant polyphenols to enhance the nutritional and sensory properties of chocolates. Food Chem 2016;200:46–54.

[68] Djamaan A, Noviza D, Septianingsih D, Suardi M. The use of purple sweet potato (*Ipomoea batatas*) starch as binder in mangosteen peel extracts lozenges formulation. Der Pharma Chemica 2016;8:410–4.

[69] Foiklang S, Wanapat M, Norrapoke T. Effect of grape pomace powder, mangosteen peel powder and monensin on nutrient digestibility, rumen fermentation, nitrogen balance and microbial protein synthesis in dairy steers. Asian-Australas J Anim Sci 2016;29:1416–23.

[70] Polyorach S, Wanapat M, Cherdthong A, Kang S. Rumen microorganisms, methane production, and microbial protein synthesis affected by mangosteen peel powder supplement in lactating dairy cows. Trop Anim Health Prod 2016;48:593–601.

[71] Hidanah S, Warsito SH, Nurhajati T, Lokapirnasari WP, Malik A. Effects of mangosteen peel (*Garcinia mangostana*) and ginger rhizome (*Curcuma xanthorrhiza*) on the performance and cholesterol levels of heat-stressed broiler chickens. Pak J Nutr 2017;16:28–32.

[72] Theapparat Y, Khongthong S, Rodjan P, Lertwittayanon K, Faroongsarng D. Physicochemical properties and in vitro antioxidant activities of pyroligneous acid prepared from brushwood biomass waste of Mangosteen, Durian, Rambutan, and Langsat. J For Res 2019;30:1139–48.

[73] Ismed Sylvi D, Rahmi ID, Wilianda C. Effects of temperature and storage time on film with mangosteen (*Garcinia mangostana* L.) peel extract as smart packaging in detecting spoilage on chicken nugget. Res J Pharm Biol Chem Sci 2016;7:1470–8.

[74] Hemachandran H, Anantharaman A, Mohan S, Mohan G, Kumar DT, Dey D, et al. Unraveling the inhibition mechanism of cyanidin-3-sophoroside on polyphenol oxidase and its effect on enzymatic browning of apples. Food Chem 2017;227:102–10.

[75] Abdul-Rahman A, Goh H-H, Loke K-K, Noor NM, Aizat WM. RNA-seq analysis of mangosteen (*Garcinia mangostan*a L.) fruit ripening. Genomics data 2017;12:159–60.

[76] Mamat SF, Azizan KA, Baharum SN, Noor NM, Aizat WM. ESI-LC-MS based-metabolomics data of mangosteen (*Garcinia mangostana* Linn.) fruit pericarp, aril and seed at different ripening stages. Data Brief 2018;17:1074–7.

[77] Palapol Y, Ketsa S, Stevenson D, Cooney J, Allan A, Ferguson I. Colour development and quality of mangosteen (*Garcinia mangostana* L.) fruit during ripening and after harvest. Postharvest Biol Technol 2009;51:349–53.

[78] Kusumawati N, Santoso AB, Sianita MM, Muslim S. Extraction characterization and application of natural dyes from the fresh mangosteen (*Garcinia mangostana* L.) Peel. Int J Adv Sci Eng Inf Technol 2017;7:878–84.

[79] Faiz F, Ngo J, Bujang K. Ascorbic acid treatment to improve the light fastness or as reducing agent on silk fabric dyed with pulverised natural dyes. Res J Textile Apparel 2016;20:74–86.

[80] Tontapha S, Sang-aroon W, Kanokmedhakul S, Promgool T, Amornkitbamrung V. Effects of dye-adsorption solvents, acidification and dye combination on efficiency of DSSCs sensitized by α-mangostin and anthocyanin from mangosteen pericarp. J Mater Sci: Mater Electron 2017;28:7454–67.

[81] Chaiamornnugool P, Tontapha S, Phatchana R, Ratchapolthavisin N, Kanokmedhakul S, Sang-aroon W, et al. Performance and stability of low-cost dye-sensitized solar cell based crude and pre-concentrated anthocyanins: Combined experimental and DFT/TDDFT study. J Mol Struct 2017;1127:145–55.

[82] Jun H, Arof A. Performance of natural dyes as sensitizer in dye-sensitized solar cells employing LiBOB-based liquid electrolyte. Ionics 2018;24:915–22.

[83] Abraham N, Rufus A, Unni C, Philip D. Nanostructured ZnO with bio-capping for nanofluid and natural dye based solar cell applications. J Mater Sci: Mater Electron 2017;28:16527–39.

[84] Zhang J, Yu S-H. Carbon dots: large-scale synthesis, sensing and bioimaging. Mater Today 2016;19:382–93.

[85] Yang R, Guo X, Jia L, Zhang Y, Zhao Z, Lonshakov F. Green preparation of carbon dots with mangosteen pulp for the selective detection of Fe^{3+} ions and cell imaging. Appl Surf Sci 2017;423:426–32.

[86] Aji MP, Wiguna PA. Facile synthesis of luminescent carbon dots from mangosteen peel by pyrolysis method. J Theor App Phys 2017;11:119–26.

[87] Ratan JK, Kaur M, Adiraju B. Synthesis of activated carbon from agricultural waste using a simple method: characterization, parametric and isotherms study. Mater Today Proc 2018;5:3334–45.

[88] Leong KH, Aziz AA, Kang YL, Goh SW, Singh KV, Sim LC, et al. Synergized mechanistic and solar photocatalysis features of N-TiO_2 functionalised activated carbon. AIMS Mater Sci 2017;4:800–13.

[89] Ruthiraan M, Abdullah E, Mubarak N, Noraini M. A promising route of magnetic based materials for removal of cadmium and methylene blue from waste water. J Environ Chem Eng 2017;5:1447–55.

[90] Hong X, Fang C, Tan M, Zhuang H, Liu W, Hui K, et al. Longan seed and mangosteen skin based activated carbons for the removal of Pb (II) ions and rhodamine-B dye from aqueous solutions. Desalin Water Treat 2017;88:154–61.

[91] Sawekwiharee S, Pechprasarn S, Kuttiyawong A, Albutt N. Adsorption of Pb (II) from solution by mangosteen peel charcoal powder. Appl Mech Mater 2017;866:116–8.

[92] Nasrullah A, Bhat A, Isa MH, Danish M, Naeem A, Muhammad N, et al. Efficient removal of methylene blue dye using mangosteen peel waste: kinetics, isotherms and artificial neural network (ANN) modelling. Desalin Water Treat 2017;86:191–202.

[93] Nasrullah A, Bhat A, Naeem A, Isa MH, Danish M. High surface area mesoporous activated carbon-alginate beads for efficient removal of methylene blue. Int J Biol Macromol 2018;107:1792–9.

[94] Giraldo L, Moreno-Piraján JC. CO_2 adsorption on activated carbon prepared from mangosteen peel. J Therm Anal Calorim 2017;133:337–54.

[95] Qi LA, Mazrul Nizam AS, Asmadi A. Influence of mangosteen pericarp (MP) in coagulation treatment and membrane fouling. Chem Eng Trans 2017;56:1843–8.
[96] Pangsupa W, Hunsom M. Preparation of mangosteen shell-derived activated carbon via KOH activation for adsorptive refining of crude biodiesel. J Am Oil Chem Soc 2016;93:1697–708.
[97] Xue M, Chen C, Ren Z, Tan Y, Li B, Zhang C. A novel mangosteen peels derived hierarchical porous carbon for lithium sulfur battery. Mater Lett 2017;209:594–7.
[98] Xue M, Chen C, Tan Y, Ren Z, Li B, Zhang C. Mangosteen peel-derived porous carbon: synthesis and its application in the sulfur cathode for lithium sulfur battery. J Mater Sci 2018;53:11062–77.
[99] Wang K, Jin Y, Sun S, Huang Y, Peng J, Luo J, et al. Low-cost and high-performance hard carbon anode materials for sodium-ion batteries. ACS Omega 2017;2:1687–95.
[100] Moopayuk W, Tangboriboon N. Anti-microbial and self-cleaning of natural rubber latex gloves by adding mangosteen peel powder. Key Eng Mater 2018;777:3–7.
[101] Chuysinuan P, Techasakul S, Suksamrarn S, Wetprasit N, Hongmanee P, Supaphol P. Preparation and characterization of electrospun polyacrylonitrile fiber mats containing *Garcinia mangostana*. Polym Bull 2018;75:1311–27.
[102] Sriyanti I, Edikresnha D, Munir MM, Rachmawati H, Khairurrijal K. Mater Sci Forum. Trans Tech Publ; 2017. p. 11–4.
[103] Sriyanti I, Edikresnha D, Rahma A, Munir MM, Rachmawati H. Correlation between structures and antioxidant activities of polyvinylpyrrolidone/*Garcinia mangostana* L. extract composite nanofiber mats prepared using electrospinning. J Nanomater 2017;2017:10.
[104] Xu W-K, Jiang H, Yang K, Wang Y-Q, Zhang Q, Zuo J. Development and in vivo evaluation of self-microemulsion as delivery system for α-mangostin. Kaohsiung J Med Sci 2017;33:116–23.
[105] Hossen S, Hossain MK, Basher MK, Mia MNH, Rahman MT, Uddin MJ. Smart nanocarrier-based drug delivery systems for cancer therapy and toxicity studies: a review. J Adv Res 2019;15:1–18.
[106] Pratiwi L, Fudholi A, Martien R, Pramono S. Design and optimization of self-nanoemulsifying drug delivery systems (SNEDDS) of ethyl acetate fraction from mangosteen peel (*Garcinia mangostana* L.). Int J PharmTech Res 2016;9:380–7.
[107] Pratiwi L, Fudholi A, Martien R, Pramono S. Self-nanoemulsifying Drug Delivery System (Snedds) for topical delivery of mangosteen peels (*Garcinia mangostana* L.,): Formulation design and *in vitro* studies. J Young Pharm 2017;9:341–6.
[108] Priani SE, Mela KA, Lukmayani Y. Development sunscreen microemulsion gel containing n-hexane fraction of mangosteen pericarp (*Garcinia mangostana* Linn.). Res J Pharm Biol Chem Sci 2017;8:229–35.
[109] Astuti KW, Wijayanti NPAD, Prasetia IGNJA. Development of gel dosage form of ethyl acetate extract of mangosteen rind (*Garcinia mangostana* L.). J Health Sci Med 2017;1:28–32.
[110] Phunpee S, Suktham K, Surassmo S, Jarussophon S, Rungnim C, Soottitantawat A, et al. Controllable encapsulation of α-mangostin with quaternized β-cyclodextrin grafted chitosan using high shear mixing. Int J Pharm 2018;538:21–9.
[111] Winuprasith T, Khomein P, Mitbumrung W, Suphantharika M, Nitithamyong A, McClements DJ. Encapsulation of vitamin D3 in pickering emulsions stabilized by nanofibrillated mangosteen cellulose: Impact on in vitro digestion and bioaccessibility. Food Hydrocoll 2018;83:153–64.
[112] Xin Lee K, Shameli K, Miyake M, Kuwano N, Khairudin BA, Bahiyah N, et al. Green synthesis of gold nanoparticles using aqueous extract of *Garcinia mangostana* fruit peels. J Nanomater 2016;2016:1–7.
[113] Park JS, Ahn E-Y, Park Y. Asymmetric dumbbell-shaped silver nanoparticles and spherical gold nanoparticles green-synthesized by mangosteen (*Garcinia mangostana*) pericarp waste extracts. Int J Nanomedicine 2017;12:6895–908.
[114] Zhang X, Xiao C. Biofabrication of silver nanoparticles and their combined effect with low intensity ultrasound for treatment of lung cancer. J Photochem Photobiol B: Biol 2018;181:122–6.
[115] Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise. J Adv Res 2016;7:17–28.
[116] Prabhu Y, Rao KV, Sai VS, Pavani T. A facile biosynthesis of copper nanoparticles: a micro-structural and antibacterial activity investigation. J Saudi Chem Soc 2017;21:180–5.
[117] Fairchild D. The mangosteen: "Queen of Fruits" now almost confined to Malayan Archipelago, but can be acclimated in many parts of tropics—Experiments in America—Desirability of widespread cultivation. J Hered 1915;6:339–47.

Dr. Wan Mohd Aizat completed his Bachelor (Hons) and PhD degrees at the University of Adelaide, Australia, specializing in the Biotechnology and Plant Science fields. He is presently assuming a research fellow/senior lecturer position at the Institute of Systems Biology (INBIOSIS), Universiti Kebangsaan Malaysia (UKM). His laboratory utilizes multi-omic approaches to decipher intrinsic regulatory mechanisms in tropical plants, such as the *Persicaria minor* herbal species and mangosteen fruit (*Garcinia mangostana*), upon various biotic and abiotic cues. Currently, he is embarking on systems biology-driven approaches to model biological systems/networks and is applying various natural products in the pharmaceutical and medicinal fields.

Faridda Hannim Ahmad-Hashim is a Senior Science Officer at the Institute of Systems Biology (INBIOSIS), Universiti Kebangsaan Malaysia (UKM). She obtained her Bachelor of Science (Environmental Biotechnology) (Hons) degree from the International Islamic University Malaysia (IIUM). She has been involved in various molecular and biotechnology works during completion of her degree and as a permanent staff at the institute. Currently, she is focusing on utilizing mangosteen fruit in various food products and applications.

Sharifah Nabihah Syed Jaafar is a Senior Lecturer at the Universiti Kebangsaan Malaysia (UKM). She received her Bachelor and master's degrees from UKM and her PhD from the University of Natural Resources and Life Sciences (BOKU), Austria. She is a life-long member of the Malaysian Solid-State Science and Technology Society (MASS). Her research interests are biorefining, renewable chemistry, and biomaterials. She has received eight awards for various studies, both nationally and internationally. She was also honored as a Young Woman in Science (Materials Science) by the Venus International Foundation in 2017 and awarded an Australian-APEC Women Research fellowship in 2018.