https://doi.org/10.1590/1678-992X-2025-0029

ISSN 1678-992X

Scientia Agricola

Food Science and Technology

Banana waste and its circularity potential: a sustainable source of alternative foods, bioactive compounds, and food technological applications

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Edited by: Carmen Josefina Contreras-Castillo

Received January 30, 2025
Accepted April 25, 2025

ABSTRACT: Bananas rank among the most widely consumed fruits globally. However, their cultivation generates substantial waste, including peels, leaves, inflorescences, and pseudostems, with up to 80 % of the plant's biomass being discarded. This waste not only poses considerable environmental and economic challenges but also represents an underutilized resource rich in unique nutritional and bioactive compounds, such as neurotransmitters, essential fatty acids, enzymes, and flavor constituents that are common in other agricultural byproducts. In this review, we present recent statistics on banana production and waste generation, alongside an examination of the potential applications of banana waste. These applications include direct consumption to combat malnutrition, incorporation into functional foods, the development of innovative food packaging, and contributions to sustainable agriculture. Additionally, we address the cultural significance of banana waste, review current life cycle analysis studies that highlight its environmental benefits, and outline the strategies for its valorization, addressing commercial viability, technical challenges, and regulatory considerations. By elucidating the processing challenges and multifunctional potential of banana waste in food science and technology, this study provides a comprehensive roadmap for leveraging this abundant resource to advance sustainable development goals, minimize agricultural waste, enhance global nutrition, and promote eco-friendly technological innovations.

Keywords: Agricultural waste, functional food, valorization, bio-packaging, sustainable development goals

Introduction

The 2030 Agenda for Sustainable Development, adopted by the United Nations in 2015, provides a comprehensive framework aimed at fostering global peace, prosperity, and environmental preservation. A critical aspect of this endeavor involves addressing carbon emissions associated with food and agricultural waste, which is crucial for mitigating climate change (Mohd Zaini et al., 2023a). In addition to energy-related carbon emission, a recent study, conducted with the support of the Global Methane Hub and the ClimateWorks Foundation, highlights the potential for innovative approaches within three pivotal areas of the food system, namely livestock, food loss and waste, and rice cultivation, to reduce carbon dioxide equivalent emissions by over 5.6 gigatons by 2050 (Buzby, 2023).

The banana (*Musa* × *paradisiaca* L.) industry, a cornerstone of tropical agriculture, highlights several challenges faced in this sector. Bananas are cultivated in over 130 countries and rank as the second most-produced fruit globally (16 % of total fruit production) and the fourth most significant agricultural commodity in developing countries. Moreover, they serve as a vital source of income for rural households (Alzate Acevedo et al., 2021). However, it is estimated that up to 80 % of the banana plant's biomass, including peels, pseudostems, and leaves, is typically regarded as waste, creating notable environmental and economic challenges (Castillo et al., 2023). Each banana tree produces fruit only once, and the leaves require regular trimming throughout the plant's lifecycle (Alzate Acevedo et al., 2021), which further contributes to biomass accumulation.

Despite innovative research focused on transforming banana waste into value-added products, current studies highlight significant nutritional and non-nutritional gaps that limit its full potential. Specifically, underexplored bioactive compounds, including neurochemicals, sterols, triterpenes, essential fatty acids, flavor compounds, and various antioxidants, remain underutilized in banana inflorescences, pseudostems, and other byproducts. While traditional culinary practices have integrated edible banana waste to combat malnutrition in underprivileged communities, modern food systems have yet to adopt these direct applications on a large scale. Furthermore, challenges persist in optimizing the use of banana waste in both traditional and contemporary food packaging. Life cycle analyses suggest promising environmental benefits, but further validation under industrial conditions is necessary. This article explores the current and potential applications of banana waste within food systems and related sectors, advocating for targeted research to address existing gaps in bioactive compound profiling, direct culinary applications, and sustainable packaging solutions, thereby paving the way toward a circular economy model for banana waste.

Global importance of banana production and its waste

Bananas are cultivated in over 1,000 varieties worldwide, although global trade primarily focuses on a few key types. These varieties can be broadly classified into dessert bananas and cooking bananas, also known as plantains. The Cavendish banana, a dessert variety, dominates the market, accounting for 47 % of global production due to its resilience and high yield (FAO, 2025). Approximately 5.6 million hectares are devoted to banana cultivation globally, with productivity levels varying significantly. Cavendish varieties typically yield between 40 and 50 metric tons per hectare, whereas smaller producers or those growing local varieties may produce only 11 and 13 metric tons per hectare. In contrast to dessert bananas, plantains are starchy and require cooking, making them a dietary staple in many parts of the world. For comprehensive information on banana cultivars, the Multilingual Multiscript Plant Name Database provides an extensive knowledge base on banana cultivars and a detailed checklist of varieties (https://www.plantnames.unimelb.edu.au/Sorting/Musa.html#intro).

Bananas are cultivated in over 135 countries and territories, particularly within the tropical and subtropical regions of Latin America, Africa, Asia, and Oceania (Ritchie et al., 2023). In many countries, bananas serve as a vital source of income for smallholder farmers. Research from ten major banana-producing nations indicates that banana farming may contribute up to 75 % of a farmer's monthly household income, making it an essential lifeline for millions (FAO, 2025). Global consumption levels of bananas are notably high. For instance, *per capita* consumption stands at approximately 60 kg annually in both the Philippines and Brazil. In contrast, several African countries, such as Uganda, Rwanda, and Cameroon, report *per capita* consumption exceeding 200 kg annually, which encompasses plantains and non-Cavendish varieties. In rural areas of these regions, bananas contribute up to 25 % of daily caloric intake, highlighting their importance as a staple food. Globally, over 100 billion bananas are consumed annually (FAO, 2025).

According to data from 2022, Asia has dominated global banana production, with an output of 69.95 million metric tons, followed by Africa (30.85 million metric tons), South America (18.98 million metric tons), North America (13.15 million metric tons), Oceania (1.57 million metric tons), and Europe (613,040 metric tons). This production trend has remained consistent since data collection began in 1961, with Asia consistently holding the position as the largest producer. Within Asia, India, and China stand out as the top contributors, with production figures of 34.53 million metric tons and 11.78 million metric tons, respectively, in 2022 (Ritchie et al., 2023). An overview of banana production is illustrated in Figure 1. The Banana Market Review 2023, published by the Food and Agriculture Organization (FAO), offers a comprehensive analysis of the global banana trade, highlighting developments, challenges, and market trends (FAO, 2024). Overall, while some key exporting countries have experienced growth, others have encountered negative trends due to external factors, including adverse weather conditions, rising production costs, and plant diseases (FAO, 2024).

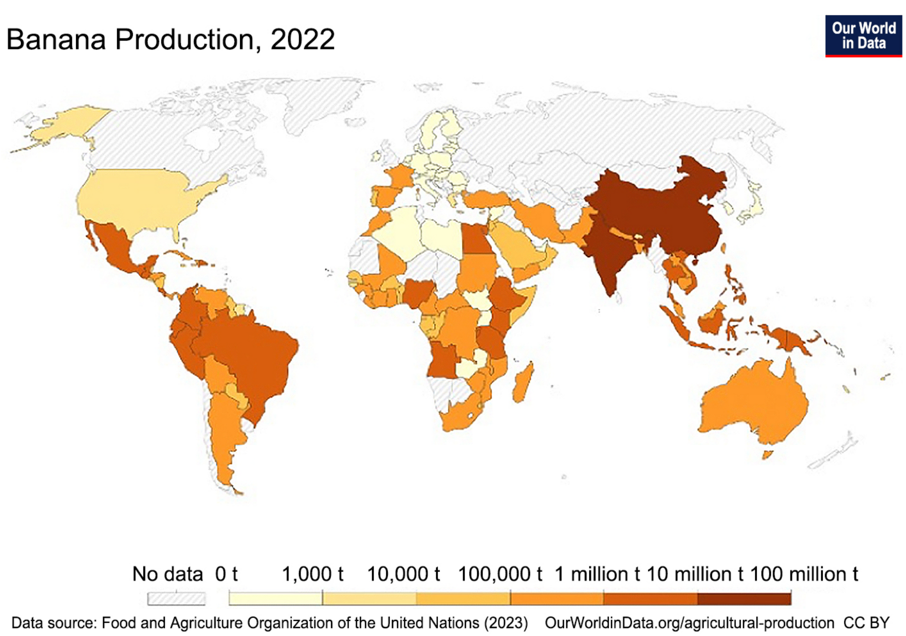

Figure 1 – Banana production worldwide. The data includes sweet/dessert bananas like *Musa sapientum*, *M. cavendishii*, and *M. nana*. It excludes plantains and cooking bananas. The information is sourced from the Our World in Data (Ritchie et al., 2023).

Banana waste and its direct applications as food

Bananas are cultivated year-round in warm climates and can grow up to 15 m tall, categorizing them as tree-like perennial herbs (Castillo et al., 2023). Approximately 30-40 % of banana fruits are rejected for not meeting quality standards (Hikal et al., 2022). Of the total weight of the banana tree, only about 12 % (the fruit) is consumed, resulting in approximately 220 tons of waste per hectare (Nascimento et al., 2021). For every kg of bananas produced, an additional 3 kg of pseudostem, 0.15 kg of rachis, and 0.48 kg of leaf waste are generated (Figure 2A-F). With 5.6 million hectares dedicated to banana cultivation in 2017, as reported by FAOSTAT, this results in a significant potential waste of around 1.2×10^7 metric tons of unused biomass. Improper disposal of this waste contributes to environmental issues, including greenhouse gas (GHG) emissions, the spread of pathogens, and leachate production, further exacerbating pollution (Castillo et al., 2023).

Banana peels

Banana peels, which constitute a significant portion of the banana fruit, are often discarded without proper treatment, leading to adverse environmental impacts and economic losses. While ripe bananas are frequently consumed in their natural state, a significant amount of bananas are processed industrially to create products such as banana chips and other long-lasting products. Notably, banana peels can constitute approximately 40 % of the total weight of fresh banana fruit (Kumari et al., 2023). Currently, the banana sector produces over 57.6 million metric tons of banana peel annually (Bhavani et al., 2023), underscoring the urgent need for effective waste utilization strategies.

The proximate composition of banana peel typically reveals a moisture content ranging from 22 % to 50 %, with fiber accounting for approximately 20 %, and carbohydrates and ash levels ranging from 8 % to 15 %. Protein content is generally below 10 %, while fat content generally remains below 2 %. In contrast, banana leaves, inflorescence, and pseudostem are predominantly composed of fiber and carbohydrates, which include cellulose, hemicellulose, and lignin, with some components exceeding 50 % in some instances (Amornlerdpison et al., 2021; Mydhili et al., 2022; Pyar and Peh, 2018). Although the components of banana waste are primarily valued for their high fiber and carbohydrate content, their potential applications extend beyond industrial uses. In particular, some of these materials are suitable for direct consumption as food, offering both nutritional and functional benefits.

The use of banana peels in food products has been investigated for their potential health and sensory attributes. These peels have been incorporated into various food items as a functional ingredient, enhancing fiber content and antioxidative properties (Kraithong and Issara, 2021; Naik and Sudheer, 2021). For instance, bakery and pasta products have been developed by replacing 5-20 % of wheat flour with banana peel flour (Segura-Badilla et al., 2022). Sensory

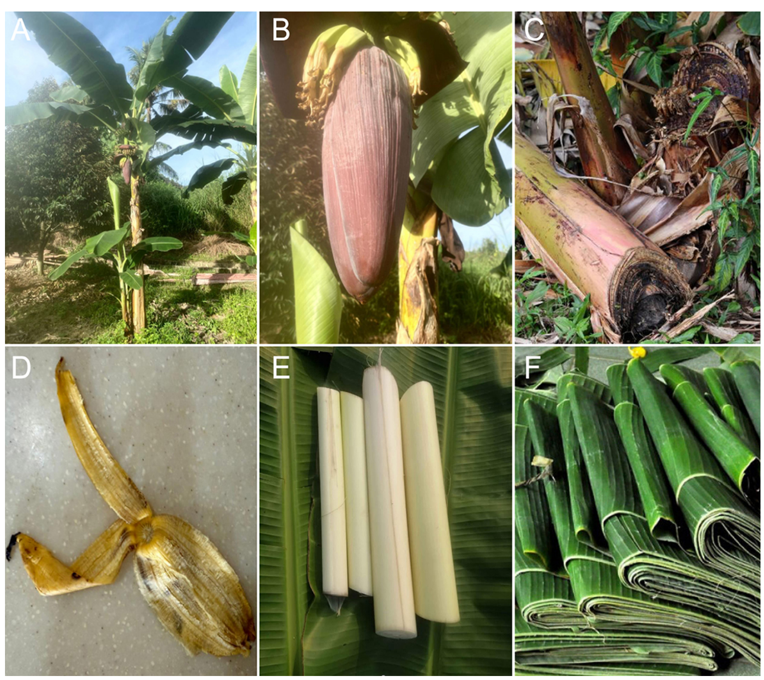

Figure 2 – Banana and its associated by-products. Clockwise from top left: (A) Whole banana plant, (B) Banana inflorescence, (C) Banana pseudostem, (D) Banana peel, (E) Cleaned banana pseudostem post-harvest (for cooking), and (F) Banana leaves traditionally used for packaging.

evaluations revealed that incorporation levels of up to 10 % flour are viable, resulting in a significant increase in fiber content while ensuring an acceptability index above 80 % (Segura-Badilla et al., 2022). Similarly, the addition of banana peel powder to sausages enriched their nutritional profile by increasing dietary fiber and reducing fat content (Mohd Zaini et al., 2020).

Banana peels are a rich source of essential components, including pectin (10-21 %), lignin (6-12 %), cellulose (7.6-9.6 %), hemicelluloses (6.4-9.4 %), and galacturonic acid (Mohapatra et al., 2010). The pectin extracted from banana peels shows potential for use as a natural thickener in whey protein isolates and orange juice (Rivadeneira et al., 2020). Additionally, pectin derived from unripe banana peels presents a promising fat replacer in baked products, such as muffins (Ahsan et al., 2024). This could serve as a cost-effective alternative to conventional pectin sources like citrus peels and apple pomace. Nevertheless, the variability among banana cultivars and the rapid deterioration during processing underscore the need for optimized extraction techniques and consistent standards (Putra et al., 2022).

Green bananas, along with their peels (which are often discarded) are recognized for their high resistant starch content, which functions similarly to soluble fiber. This attribute benefits gut health and promotes a feeling of satiation, making green bananas particularly advantageous for individuals monitoring their sugar intake, as they contain less sugar compared to ripe bananas (Wang et al., 2014). Moreover, specific vitamins, minerals, and antioxidants present in young bananas are more stable and may diminish as the fruit ripens (Wang et al., 2014). However, the flavor profile of these young bananas, especially in their peels, can be astringent and less sweet, which may not appeal to everyone. Therefore, to mitigate this astringency, coconut milk is often employed in some regions of Southeast Asia, as its rich flavor complements the bananas. Coconut milk, a plant-based milk commonly cultivated in impoverished areas, is renowned for its versatility and enhances the dish's nutritional profile with its substantial content of healthy fatty acids, such as lauric acid, and proteins (Gengan et al., 2024; Abd Rahim, 2025). This culinary practice offers an economical, nutrient-rich, and sustainable source of fats, proteins, dietary fiber, and micronutrients. This is particularly significant given that many of these plantations are situated in underprivileged rural areas, aligning with Goal 2.1 of ensuring adequate nutrition (FAO, 2025).

In the pursuit of circularity, the utilization of fruit peels aligns with numerous criteria for sustainable food production. Different fruit peels serve distinct purposes: both banana and citrus peels are rich in pectin and antioxidant flavonoids. For instance, banana peel pectin boasts a high methoxyl content and excellent gelling properties that are comparable to those of citrus pectin (Khamsucharit et al., 2018). However, citrus peels typically contain higher levels of essential oils, which exhibit potent antimicrobial activity. One study demonstrated that lemon peel powder outperformed banana peel in inhibiting the growth of meat spoilage microbes (Abdel-Naeem et al., 2022). In contrast, banana peels offer the unique advantage of a higher starch content, particularly in unripe peels, making them ideal for producing bioplastic materials or serving as a source of functional dietary fiber.

Banana leaves

Banana leaves are large, flexible, and waterproof, and they have historically held significant cultural importance across various cultures worldwide. The deep green leaves of the banana plant carry both culinary value and cultural importance (Sarin, 2021). Although they are biodegradable, improper disposal or burning of banana leaves can lead to environmental issues, including GHG emissions and soil degradation (Castillo et al., 2023).

In many tropical and subtropical regions, banana leaves are intricately woven into daily life, being utilized as eco-friendly plates, cooking wraps, and even decorative elements (Kraithong and Issara, 2021). Generously sized at approximately 2.7 × 0.6 m, banana leaves have remarkable qualities, including waterproofing, flexibility, and impermeability (Sarin, 2021). These features make them ideal for both food packaging and serving. Furthermore, the use of banana leaves is regarded as hygienic, safe, and nutritious, as they enhance the flavor of food due to their wax-like coating, which prevents dirt and dust from adhering (Sarin, 2021). Recently, there has been a growing interest in employing banana leaves as a sustainable alternative to plastic packaging, leading to preservation methods that can maintain their properties for up to six months. Studies indicate that these products exhibit increased tensile strength and strong fiber-matrix interfacial interaction within the composites (Arumugam et al., 2023).

Although banana leaves are not typically consumed as food, they play a crucial role in traditional food packaging. Utilizing banana leaves for this purpose helps to preserve cultural heritage while promoting sustainable practices (Kraithong and Issara, 2021). In India, particularly in the southern states of Tamil Nadu, Karnataka, Kerala, Andhra Pradesh, and Telangana, the tradition of serving meals on banana leaves is both deeply rooted and distinctive. Their generous size accommodates a wide variety of dishes, including rice, curries, chutneys, and sweet delicacies (Sarin, 2021). In tropical regions of Mexico, tamales are traditionally wrapped in banana leaves, while in Balinese Hindu culture, they are used as containers for floral offerings to spirits and deities (Sarin, 2021). In Malaysia, the national dish "Nasi Lemak" and various delicacies are often wrapped in banana leaves, which enhances both their flavor and the overall dining experience (Raji et al., 2017).

In various cultures, especially in Southeast Asia, the banana leaves are often heated before use. When exposed to heat, these leaves undergo several physicochemical changes that impact their suitability for packaging. One significant effect is the release of distinctive aromatic compounds, which is evident in many Southeast Asian dishes that utilize these leaves as wrappers for cooking. Furthermore, banana leaves have a naturally waxy surface layer. Heating causes a gentle melting of this layer, increasing the leaf's flexibility and creating a semi-sealed environment that is crucial for preserving moisture and flavor in the packaged food. However, excessive exposure to high temperatures can lead to brittleness and a decrease in tensile strength. However, under controlled moderate heating, the leaves maintain or even improve their malleability, which is essential for practical wrapping purposes (Balasubramanian, 2022; Sarin, 2021).

Pseudostems

As banana leaves grow, the sheaths accumulate and undergo a thickening process that leads to the formation of the fibrous components known as the pseudostem. This pseudostem can attain heights of 6 to 7.6 m, which supports the development of fruits, flowers, and foliage. The growth process continues until the plant reaches its full height, typically ranging from 2 to 8 m. A mature pseudostem is distinguished by its robust and succulent composition, which can be divided into four distinct stages, each contributing varying proportions: (a) exterior (approximately 41 %); (b) intermediate (approximately 27 %); (c) internal (approximately 21 %); and (d) shell (11 %) (Subagyo and Chafidz, 2018). The lignocellulose fiber content of the banana pseudostem, when assessed on a wet basis, ranges from 1.6 % to 8 %, and can reach up to 30 % on a dry weight basis (Aziz et al., 2011). The remaining proportion is comprised of the parenchyma, which can reach a maximum value of 4 % (Mamun et al., 2015). Notably, the pseudostem constitutes 60.5 % of the banana plant's total mass and is rich in cellulose, hemicellulose, and lignin, all of which possess valuable functional and mechanical properties (Castillo et al., 2023). Nevertheless, this part of the plant is typically discarded on the plantation or incinerated, leading to waste production and GHG emissions.

The transformation of banana pseudostem into flour for culinary applications is a common practice due to its high carbohydrate content, significant fiber content and functional properties. Pseudostems are particularly rich in calories, functional carbohydrates, minerals, and vitamins, rendering them a valuable resource for therapeutic uses. With complex carbohydrate levels reaching up to 50 %, banana pseudostems can also serve as prebiotics, promoting gut health and thereby enhancing overall well-being.

For instance, a low-calorie juice rich in antioxidants has been developed from the banana pseudostem (Pillai et al., 2024). Additionally, fortified biscuits with sensory attributes (taste and crispiness) comparable to those of control biscuits have been created by partially replacing wheat flour with pseudostem core flour (Chakraborty et al., 2021). These studies highlight the potential of banana pseudostems in the development of functional foods enriched with nutraceutical and antioxidant properties.

In regions with high banana production, utilizing banana byproducts can aid in addressing nutrient deficiencies, mainly since many major banana-producing countries, such as Ecuador and the Philippines, are still classified as developing countries (FAO, 2025). The potential of banana peel and pseudostem as dietary components for humans is particularly evident in certain Southeast Asian regions, where young bananas, along with their peels and pseudostems, are incorporated into rich curries based on coconut milk. The pseudostem boasts a nutrient profile that includes dietary fiber, potassium, calcium, vitamins A and C, as well as various other bioactive compounds, suggesting potential health benefits for human consumption (Pillai et al., 2024).

A biodegradable polyvinyl alcohol film reinforced with cellulose derived from banana pseudostem has been developed for grape packaging (Ghosh and Ghosh, 2020). Due to its high carbohydrate content, the extracted cellulose, in the form of nano-cellulose, has a wide range of applications. These include biodegradable food packaging, food preservation utilizing a polysaccharide-based Pickering stabilizer, serving as an antioxidant-rich textural enhancer and fat replacer, encapsulating to reduce fat digestion and improve probiotic delivery, and enriching dietary fiber in functional foods (Mohd Zaini et al., 2022a). The polysaccharides exhibit low amylase activity, solubility, and retrogradation, making them particularly suitable for gelling, thickening, and stabilizing food formulations (Padam et al., 2014). Nevertheless, it is possible to obtain functional biopolymers, such as polyhydroxybutyrates and poly-L-lactic acid, with appropriate treatments (Mohd Basri et al., 2021; Redondo-Gómez et al., 2020).

A noteworthy study explores the diverse environmental implications of utilizing lignocellulosic banana stems via Life Cycle Analysis (LCA). In the context of Colombia, bio-composites derived from banana pseudostems not only provide cost advantages but also exhibit a diminished environmental footprint compared to traditional polyester. However, these benefits come with trade-offs. Specifically, the bio-composites show compromised tensile strength and heightened water absorption capabilities. Interestingly, a mixture containing 15 % banana fiber, combined with kaolinite, without the addition of any chemical pretreatments, demonstrated both lower production costs and diminished environmental impacts (Rodríguez et al., 2018).

Several researchers have conducted LCA studies on the environmental impact of banana waste in bio-packaging. One study found that when lids integrated with 40 % banana fiber outperformed those made solely with Polylactic Acid (PLA) across all evaluated impact categories. Furthermore, when compared directly with lids made exclusively from high-density polyethylene (HDPE), the banana fiber-infused variants demonstrated superiority in three key areas. This evidence supports a strong environmental rationale for partially replacing traditional PLA with banana fiber, especially in lid production (Rodríguez et al., 2020). Additionally, findings from other LCA studies indicate that the environmental benefits of biocomposites (specifically recycled high-density polyethylene) can be further optimized by increasing the filler concentration, particularly when these composites are produced through extrusion and hot press techniques (Cabrera et al., 2023).

In a notable study, a combined LCA was performed on the valorization of banana pseudostem into molded clamshells for food packaging and liquid banana fertilizer (Castillo et al., 2023). The LCA results revealed that integrating these processes led to a four-fold reduction in environmental impact compared to traditional expanded polystyrene (EPS) clamshells, and a remarkable 99 % reduction in the effects of traditional urea ammonium nitrate (UAN) fertilizers. The study also highlighted the importance of the plant location and the energy sources utilized during production, suggesting that renewable energy serves as an optimal choice to mitigate further the environmental impacts associated with pulp refining and molding.

The use of banana pseudostems in food science and technology remains relatively limited. Most applications have tended to non-food purposes, primarily due to the inherent fiber strength of the pseudostem. These applications encompass a range of products, including ropes, textiles, baby diapers, bags, filter cloths, insulation, natural absorbents, and reinforcement fibers (Subagyo and Chafidz, 2018). To render banana pseudostems suitable for these applications, a comprehensive range of pretreatment processes is necessary. These processes may involve retting, the removal of lignin and cementing materials, bleaching, and degumming, all of which are essential for preparing the pseudostems for their intended applications (Subagyo and Chafidz, 2018).

Banana inflorescence

An equally important but lesser-known part of the banana plant is the inflorescence, commonly referred to as the banana flower or "blossom". This cone-shaped bud, typically dark purple-red, grows at the end of the banana fruit cluster and serves as a precursor to the fruit. As the bananas develop, the inflorescence is often discarded, leading to a significant amount of agricultural waste in banana-producing regions (Lau et al., 2020). A recent study conducted a comprehensive analysis of the proximate components found in various parts of banana waste (Kumari et al., 2023).

Banana inflorescences exhibit a unique proximate composition that highlights their nutritional value. They have a notably high moisture content, ranging from 90.10 % to 92.17 %, which contributes to their perishable nature. The protein content ranges from 1.43 % to 19.60 %, while the fat content remains relatively low, typically between 0.43 % and 0.85 %. The ash content, which indicates the presence of minerals, ranges from 1.26 % to 18.30 %. A significant component of the inflorescences is dietary fiber, with crude fiber content reported between 12.42 % and 52.16 %. Carbohydrates constitute a substantial portion, with values ranging from 16.09 % to 59.68 %. These variations in composition can be attributed to factors such as banana cultivar, environmental conditions, and processing methods. The combination of high dietary fiber and carbohydrate content, along with low fat levels, positions banana inflorescences as a nutritious food source with potential health benefits (Fingolo et al., 2012).

In Thailand, the banana flower, also known as the inflorescence, is recognized as a natural galactagogue and is traditionally used in the diets of postpartum mothers. Its potent antioxidative properties, derived from various bioactive compounds, may support healthy lactation. Research has demonstrated that these extracts significantly increase breast milk production in rats, and when processed into flour, they further enhance lactation (Amornlerdpison et al., 2021). This effect may be attributed to the presence of dopamine, which regulates neurotransmitters in the brain and affects mood, concentration, and emotional stability in postpartum mothers (Afzal et al., 2022). Additionally, the Xokleng Indians of Brazil use banana inflorescence to produce a syrup that functions as an expectorant for alleviating respiratory ailments (Correa et al., 2017). Globally, particularly in Southeast Asia, banana flowers are a common ingredient in numerous dishes and can be easily prepared by blanching (Meatless Makeovers, 2019).

Bioactive compounds from banana waste

The wide variety of bioactive polyphenolic compounds in banana waste, as demonstrated in Table 1, offers numerous nutraceutical benefits (Azman et al., 2022; Izzati et al., 2023). Compounds such as ferulic acid, quercetin, catechin, chlorogenic acid, and gallic acid have been found in banana peels, pulp, inflorescences, and pseudostems across several cultivars, including Cavendish, *M. paradisiaca*, and *M. sapientum*. These polyphenols are well-known for their antioxidant and health-promoting properties, positioning bananas as a rich source of bioactive substances suitable for functional food development and nutraceutical applications (Gengatharan and Abd Rahim, 2023; Mohd Zaini et al., 2023a).

Bananas and their various components are a rich source of sterols and triterpenes, both of which are recognized for their health-promoting properties (Table

Table 1– Potential phytochemical compounds from banana and its waste. Please note that this list is not exhaustive. Plant-based materials typically contain a variety of bioactive compounds, and some of these compounds may remain undiscovered.

Parts	Cultivar	Polyphenolic Compounds	References
Peels	Red Yade	Hydroxycinnamic acids: Ferulic acid, ferulic acid-hexoside, triferuloyl-dihexose, caffeic acid-hexoside, sinapic acid, sinapic acid-hexoside	Passo Tsamo et al., 2015
	Cavendish	Quercetin -7-rutinoside, quercetin -3-rutinoside, kaempferol-3-rutinoside, kaempferol-7-rutinoside, isorhamnetin-3-rutinoside, myricetin-3-rutinoside, laricitrin-3-rutinoside, syringetin-3-rutinoside	Rebello et al., 2014
	Musa paradaisica L.	Quercetin, coumarin, catechin, caffiec acid, cinnamic acid, chyrsin	Aboul-Enein et al., 2016
	Musa paradisiaca	Dodecanoic acid, hexadodecanoic acid, linolenic acid, linoleic acid, 18-hydroxyoleic acid, ferulic acid, caffeic acid	Corona et al., 2015
	Musa sapientum L. (Kluai Hin)	Gallic acid, gallocathechin, catechin, epicatechin, quinic acid, chlorogenic acid, glucocaffeic acid, macrocarposide, saponarin, hovenitin i, kuwanon, eriodictyol	Tongkaew et al., 2022
	Various	Phenolics: Gallic, ferulic, and caffeic acid, and tocopherols Anthocyanins: Delphinidin and cyanidin Carotenoids: α- and β-carotene, zeaxanthin, rutin, naringenin, lutein, delphinidin, isolutein, auroxanthin, violaxanthin, neoxanthin, α- and β-cryptoxanthin, and xanthophylls Flavanoids: Gallocatechi, catechin, leucocyanidin, flavanone and flavanol glycoside, quercetin, and chrysin	Hikal et al., 2022; Padam et al., 2014; Pereira and Maraschin, 2015
Pulp	Cavendish	Ferulic acid, caffeic acid, cyanidin 3,5-*o*-diglucoside, pelargonidin 3-o-(6''-succinyl-glucoside), apigenin 7-*o*-apiosyl-glucoside, scopoletin, umbelliferone	Bashmil et al., 2021
	Green Cavendish	Ferullic acid, coumaryl-hexoside, caffeic acid, chlorogenic acid, gallic acid, ellagic acid, catechin, procyanidin-b, rhamnetin, syringetin-3-glusoside	Loyola et al., 2021
	Musa acuminata (pulp)	Apigenin, caffeic acid, chlorogenic acid, kaempferol, naringenin, quercetin, rosmarinic acid, syringic acid	Kritsi et al., 2023
	Musa sapientum L. (Kluai Hin)	Gallocathechin, catechin	Tongkaew et al., 2022
	Musa accuminata Cavendish	3,5-dihydroxybenzoic acid, protocatechuic acid, hydroxybenzoic acid, 4-hydroxybenzaldehyde, benzoic acid, caffeic acid, p-coumaric acid, ferulic acid, quercetin 3,4'-o-diglucoside, quercetin 3-o-sophoroside, protocatechuic acid, gallic acid 3-o-gallate, ferulic acid, isoferulic acid	Ramírez-Bolaños et al., 2021
	Palayankodan (*Musa × paradisiaca* Mysore) Nendran (*Musa × paradisiaca*) Njalipoovan (*Musa × paradisiaca*)	Protocatechuic acid, tannic acid, 4-hydroxybenzoic acid, vannillic acid, caffeic acid, p- coumaric acid, trans-ferulic acid, trans-cinamic acid, epicatechin	Gayathry and John, 2023
	Culinary banana (*Musa* ABB)	Catechin hydrate, chlorogenic acid, vanillic acid, syringic acid, p-coumaric acid, ferulic acid, salicylic acid, quercetin dihydrate, quinic acid	Begum and Deka, 2019
	Musa acuminate	Umbelliferone (7-hydroxycoumarin)	Chiang et al., 2021
	Various	Phenolics: Gallic, tannic acid, *p*-hydroxylbenzoic acid, hydroxybenzaldehydes, protocatechuic acid, gentisic acid, vanillic acid, vanillin, caffeic acid, syringic acid, ferulic acid, *p*-coumaric acid, chlorogenic acid, sinapic acid and catechol Anthocyanins: cyanidin-3-rutinoside, proanthocyanidins Flavanoids: Catechin, epicatechin, quercetin and rutin, isoquercetin	Lau et al., 2020; Padam et al., 2014; Ramírez-Bolaños et al., 2021

Continue...

Table 1 – Continuation.

	Musa accuminata Cavendish	Protocatechuic acid, p-coumaric acid, ferulic acid	Ramírez-Bolaños et al., 2021
	Palayankodan (*Musa × paradisiaca* Mysore) Nendran (*Musa × paradisiaca*) Njalipoovan (*Musa × paradisiaca*)	Gallic acid, protocatechuic acid, vannillic acid, caffeic acid, syringic acid, p-coumaric acid, trans-ferulic acid, trans-cinnamic acid	Gayathry and John, 2023
	Pisang Awak (*Musa* spp.)	L-epicatechin, quercetin-o-rutinoside-o-rhamnoside, epiafzelechin, isorhamnetin-o-rutinoside, luteolin-7-o-rutin, eriodictyol c-hexoside, di-o-methylquercetin, kaempferol 3-o-rutinoside (nicotiflorin), quercetin 3-o-rhanosylgalactoside, 6-hydroxykaempferol7-o-glucoside	Deng et al., 2020
	Berangan (*Musa* spp.)	Quinic acid, aconitic acid, caffeoyl glucose, caffeic acid, ferulic acid glucoside, rutin, sinapic acid, p-hydroxybenzoic acid	Fung et al., 2021
Inflorescence (Banana flower)		Phenolics: Protocatechuic, caffeic, ferulic, tannins, *p*-hydroxybenzoic, vanillin, coniferin, sinapinaldehyde, and hydroxycinnamic acid Anthocyanins: (+)-Catechin and tannins Flavanoids: Rutin, L-epicatechin, and (-)-epiafzelechin	Deng et al., 2020; Padam et al., 2014; Ramírez-Bolaños et al., 2021
	Musa balbisiana	Rutin	Yingyuen et al., 2020
	Berangan (*Musa* spp.)	Quinic acid, ferulic acid, caffeoyl glucose, caffeic acid, kaempherol-rhamnose-hexose	Fung et al., 2021
	Various	Phenolics: Protocatechuic, rosmarinic, chlorogenic, cinnamic, caffeic, syringic, ellagic, vanillic, ferulic, sinapic, and hydroxycinnamic acids, and pyrogallol Flavanoids: Rutin, catechin, chrysin, quercetin, and epicatechin	Kappel et al., 2013; Padam et al., 2014; Salama et al., 2020; Sonibare et al., 2018; Yingyuen et al., 2020

2). Sterols, a class of compounds closely resembling cholesterol and commonly found in plants, have been shown to reduce cholesterol absorption in the gut, thereby promoting cardiovascular health. Triterpenes, a diverse and extensive group of chemical compounds composed of three terpene units, often exhibit anti-inflammatory and anticancer effects. Various parts of the banana plant, such as peels, leaves, inflorescences, and pseudostems, contain these compounds, each offering unique benefits for food, health, and industrial applications (Hikal et al., 2022; Padam et al., 2014; Pereira and Maraschin, 2015). The distribution of these bioactive compounds across different parts of banana wastes will be discussed in greater detail in the subsequent subchapters.

Banana peel

Existing literature suggests that various components of banana waste share overlapping characteristics due to their similar composition. Like banana pulp, banana peels are rich in organic matter, such as cellulose, pectin, hemicellulose, chlorophyll pigments, and various low-molecular-weight compounds (Kumari et al., 2023). Notably, a study has revealed that the concentration of gallocatechin in banana peels is five-fold higher than that typically found in the pulp (Someya et al., 2002). This finding is exciting, as gallocatechin is commonly associated with green tea.

A study indicated that the phenolic compounds found in the banana peel can be grouped into four subcategories: flavanols, hydroxycinnamic acids, flavan-3-ols, and catecholamines (Vu et al., 2018). The researchers also determined that the ripening stage of bananas is linked to their antioxidant capacity. Specifically, as bananas ripen, the antioxidant potential of their peels increases; however, this capacity diminishes once the bananas become overripe. Notably, overripe banana peels exhibited 11-16 % reduction in free radical scavenging activity, a 12-21 % decrease in ferric and cupric reducing power, and a 10-11 % drop in phenolic content compared to ripe fruits. Additionally, the peel loses most of its chlorophyll content and 7-17 % of its carotenoids during the over-ripening process (Vu et al., 2019).

Banana peels are notably rich in hydroxycinnamic acids and flavonoids (Table 1). The peel of the Red Yade contains ferulic acid, sinapic acid, and their derivatives, which are recognized for their antioxidant properties (Passo Tsamo et al., 2015). Cavendish peels are particularly abundant in quercetin and kaempferol rutinosides, which have been linked to anti-inflammatory and cardiovascular benefits (Rebello et al., 2014). In *M. sapientum*, compounds such as gallic acid and epicatechin are prevalent, further contributing to its antioxidant and anticancer potential (Tongkaew et al., 2022). The concentration of these polyphenols may

Table 2 – Lipid-based compounds in banana and its components. Please note that this list is not exhaustive. Plant-based materials typically contain a variety of bioactive compounds, and some of these compounds may remain undiscovered.

Parts of Banana	Cultivar	Lipid-based Compounds	References
Peels	Dwarf Cavendish	Lauric acid, palmitic acid, decanoic acid, myristic acid, linoleic acid, palmitelaidic acid, oleic acid, campesterol, stigmasterol, cycloeucalenone, β-sitosterol, triterpene ketone, cycloaeucalenol, cycloartenol, δ-tocopherol, diacylglycerols, steryl glucosides, steryl esters	Oliveira et al., 2008
	Chinese Cavendish	Dodecanoic acid, eicosanoic acid, triacontanoic acid, hexadec-9-enoic acid, octadeca-9,12-dienoic acid, nonadioic acid, hexadecan-1-ol, octadecan-1-ol, campesterol, stigmasterol, β-sitosterol	Vilela et al., 2014
	Musa paradisiaca	31-norcyclolaudenone, cycloeucalenone, stigmasterol, β-Sitosterol, 24-methylene-cycloartenol	Silva et al., 2014
Pulp	Dwarf Cavendish	Lauric acid, palmitic acid, decanoic acid, myristic acid, linoleic acid, palmitelaidic acid, oleic acid, docosanoic acid, cycloeucalenone, β-sitosterol, campesterol, stigmasterol, diacylglycerols, steryl glucosides, steryl esters, isofucosterol	Oliveira et al., 2008
	Chinese Cavendish	Dodecanoic acid, eicosanoic acid, triacontanoic acid, hexadec-9-enoic acid, octadeca-9,12-dienoic acid, nonadioic acid, hexadecan-1-ol, octadecan-1-ol, campesterol, stigmasterol, β-sitosterol	Vilela et al., 2014
	Grand Nain	Dodecanoic acid, eicosanoic acid, triacontanoic acid, hexadec-9-enoic acid, octadeca-9,12-dienoic acid, nonadioic acid, hexadecan-1-ol, octadecan-1-ol, campesterol, stigmasterol, β-sitosterol, α-tocopherol	Vilela et al., 2014
Inflorescence (Banana flower)	*Musa balbisiana* cv. Saba	31-norcyclolaudenone, cycloartenol, (24R)-4a,24-trimethyl-5a-cholesta-8,25(27)-dien3b-ol	Tin et al., 2016
	Musa spp.	β-sitosterol, 31-norcyclolaudenone, (24R)-4α, 14α, 4-trimethyl-5α-cholesta-8, 25(27)-dien-3β-ol	Sheng et al., 2017
	Musa paradisiaca L.	Progesterone	Kalwar et al., 2021
Pseudostem	*Musa sapientum*	Sterols, octadecanoic acid, benzenediol, 2,6,10-dodecatrien-1-ol	Dikshit et al., 2016
	Musa sp. cv. Nanjangud Rasa bale	Stigmasterol, β-sitosterol	Ramu et al., 2016
	Pisang Awak (*Musa* spp.)	24,30-dihydroxy-12(13)-enolupinol, 2-Hydroxyoleanolic acid, Oleanolic acid-3-O-beta-D, pyran xylose (1→3)-beta-D-pyran glucuronide, Asiatic acid, Maslinic acid	Deng et al., 2020
Leaves	*Musa sapientum* L.	Corosilic acid	Yoo et al., 2016
	Musa acuminata AAA	N-hexadecanoic acid, octadecatrienoic acid, neophytadience, 3,7,11,15-tetramethyl-2-hexadecen-1-ol, phytol	Ha Thi et al., 2024

be attributed to the protective role of the peel, which naturally accumulates defensive compounds to protect against pathogens and environmental stress (Pandey and Rizvi, 2009). While the pulp is consumed directly, it also contains bioactive compounds, although typically in lower concentrations than the peel. The reduced polyphenol content in the pulp may be attributed to its primary function, which is not defensive but nutritive, serving as a storage of energy in the form of sugars (Pandey and Rizvi, 2009).

Among bioactive compounds, catecholamines, namely dopamine, norepinephrine, gamma-aminobutyric acid (GABA), and epinephrine, are often overlooked in discussions of valuable bioactive compounds, yet they are indeed significant (Kulma and Szopa, 2007; Ramos-Ruiz et al., 2018). Primarily recognized as neurotransmitters in the central nervous system (Hajar-Azhari et al., 2018; Shin Yee et al., 2021), ripe banana peels may contain the highest levels of catecholamine compared to other plant-based foods (Kulma and Szopa, 2007). This observation aligns with the idea that the antioxidant capacity of banana peels increases with ripening (Vu et al., 2018). These compounds display remarkable antioxidant properties, rivaling those of ascorbic acid and exceeding those of glutathione and synthetic antioxidants. Their antimicrobial characteristics enhance their potential in bioactive food packaging, notably in the formulation of polydopamine coatings (Kulma and Szopa, 2007). However, it is important to note that while dietary catecholamines do not cross the blood-brain barrier, the direct application of these compounds in food products requires careful consideration, given their role as neurotransmitters in humans (Kulma and Szopa, 2007).

Banana leaves

The bioactive compounds found in leaves are primarily a result of their exposure to environmental stressors, such as ultraviolet radiation, which encourages the accumulation of protective flavonoids (Pandey and Rizvi, 2009). These leaves are particularly rich in coumarin, a compound known for its anti-inflammatory and anticoagulant properties. As a result, coumarins are frequently utilized in the food and pharmaceutical industries for their capacity to enhance blood circulation and reduce the risk of blood clots. Additionally, rutin, a well-known flavonoid renowned for its therapeutic benefits, was also identified as a significant component in banana leaves in a study conducted by Yingyuen et al. (2020) (Table 1). Their research involved a phytochemical analysis and isolation of rutin derived from an ethanolic extract of banana leaves sourced from *M. balbisiana*, achieving an impressive purity level of 98.4 %.

Banana leaves are recognized for their rich content of various bioactive lipids, which contribute to their medicinal and preservative properties. Notably, compounds such as N-hexadecanoic acid, octadecatrienoic acid, neophytadience, 3,7,11,15-tetramethyl-2-hexadecen-1-ol, and phytol are phytosterols and offer an array of health benefits, including antioxidant, anti-inflammatory, and antimicrobial properties (Ha Thi et al., 2024) (Table 2). Collectively, these compounds make banana leaves advantageous for food wrapping, as they enhance food preservation, protect against microbial spoilage, and may provide potential health benefits when used in traditional remedies.

In a separate study, epigallocatechin, a compound related to gallocatechin found in banana peels, exhibits characteristics similar to those of green tea (Someya et al., 2002) and is also abundant in banana leaves (Sagrin and Chong, 2013). This flavonoid is known for its potent antioxidant properties, ranking among the most effective in plant-based foods (Kulma and Szopa, 2007). Its potential health benefits include cardiovascular protection, cancer prevention, antimicrobial effects, and applications in skincare. When hot food is wrapped in banana leaves, it can absorb epigallocatechin, thereby providing nutritional benefits to the consumer (Sagrin and Chong, 2013).

Remarkably, the presence of 9-LOX enzymes in banana leaves confers flavors reminiscent of oolong tea, melon, and fruity cucumber, significantly enhancing the culinary experience (Padam et al., 2014). When utilized as packaging, these leaves contribute unique flavors and aromas to food, and their wax coating melts when hot food is packed, further elevating the taste (Kora, 2019). The heating process, which increases malleability, may enhance the inherent antimicrobial properties of the leaves, potentially providing an additional protective layer against specific food-borne pathogens. Concurrently, beneficial compounds, particularly polyphenols, can be released from the leaves into the food during heating, suggesting an enhanced nutritional aspect to their use. Nevertheless, unlike synthetic alternatives, banana leaves decompose without harming the environment and crucially do not release toxic substances when heated. Thus, when assessed for packaging applications, heated banana leaves present both functional benefits and environmental sustainability (Balasubramanian, 2022; Sarin, 2021).

Banana inflorescence

A comprehensive analysis of the lesser-explored aspects of banana inflorescence, including its bioactive compounds, was conducted by Lau et al. (2020) and Kraithong and Issara (2021). While the data varies among different banana cultivars, it is noteworthy that the inflorescence consistently possesses a significant carbohydrate content, which accounts for over 50 % of the total proximate values in numerous studies. Given this dominance of carbohydrates, other major nutrients, such as fats and proteins, are typically minimal, often accounting for less than 2 %. However, specific variants may exhibit higher levels of protein and ash content, potentially exceeding 10 % (Kraithong and Issara, 2021). Nevertheless, the beneficial composition of unsaturated fatty acids, comprising oleic, linoleic, and α-linolenic acids, remains limited due to the overall low-fat content, which reduces the potential cardiovascular benefits associated with the fat portion.

The inflorescence is notable for its rich carbohydrate portion, which suggests that a significant portion may be abundant in dietary fiber with bioactive potential, including compounds such as fructo-oligosaccharides, xylo-oligosaccharides, pectic-oligosaccharides, and inulin (Chockchaisawasdee and Stathopoulos, 2022). These compounds can function as functional dietary fiber beneficial for gut health or be processed into sweet syrups and powders (Lau et al., 2020). Previous research has indicated that inflorescences are rich in polysaccharides such as arabinogalactan, rhamnogalacturonan, arabinoxylan, and xyloglucan, while the alkali-insoluble residue mainly comprises cellulosic polysaccharides (Zou et al., 2022). This distinction impacts health when consumed in their natural form and has implications for industrial applications, such as the extraction of sweeteners (Zou et al., 2022).

The banana inflorescence is also rich in essential amino acids, functional carbohydrates, linoleic acid, and minerals such as potassium and iron, which contribute to its status as a nutrient-dense food. Additionally, its phytochemicals, including phenylphenalenones and coumarins, further enhance its anti-inflammatory and antioxidant properties (Lau et al., 2020; Padam et al., 2014; Ramírez-Bolaños et al., 2021) (Table 1). These attributes make banana flowers a valuable functional ingredient in health foods, offering benefits for heart health, anti-inflammatory effects, and wound healing.

Banana waste is increasingly being recognized for its potential applications as a natural colorant and sweetener, in response to the growing consumer demand for clean-label products free from synthetic additives (Jamaluddin et al., 2022). The high concentration of anthocyanins found in banana waste inflorescence (Sani, 2010), leaves (Saleh et al., 2013), and banana peels (Saleh et al., 2009) highlights its promise as a viable colorant option. Furthermore, banana bracts, which originate from the inflorescence, contain approximately 32 mg of anthocyanin per 100 g, presenting a significant opportunity as a cost-effective and edible source of natural pigments (Amutha et al., 2022).

In addition to the typical bioactive phytochemicals, the inflorescence is notably rich in bioactive lipids such as cycloartenol and progesterone, which are associated with hormone regulation and anticancer properties (Kalwar et al., 2021; Sheng et al., 2017). Inflorescence sterols, including β-sitosterol, demonstrate significant anti-diabetic potential by inhibiting enzymes like α-glucosidase (Kalwar et al., 2021; Sheng et al., 2017). Meanwhile, the leaves are abundant in corosolic acid and phytol, compounds recognized for their anti-aging and anti-diabetic effects (Ha Thi et al., 2024; Yoo et al., 2016) (Table 2).

Banana pseudostems

The banana pseudostem has a high carbohydrate content, ranging from 70 % to 80 % (Subagyo and Chafidz, 2018). Within this carbohydrate composition, cellulose is the predominant component, constituting 50 %, followed by hemicellulose and lignin. These fibers not only have widespread applications in the production of sustainable packaging but also show potential for incorporation into edible products and dietary supplements, offering valuable nutritional benefits (Subagyo and Chafidz, 2018).

Similar to the peel, the pseudostems are rich in phenolic compounds (Table 1). A recent study indicated that the phenolic content of the pseudostems can be up to eight-fold higher than that of the flowers, highlighting a significant opportunity in the sector of functional foods, especially considering the substantial waste generated compared to the flowers. Furthermore, the concentration of phenolic compounds found in banana pseudostems, such as catechin, tannic acid, gallic acid, and cinnamic acid, is comparable to that of other commonly consumed plant-based foods (Al-Mqbali and Hossain, 2019). Additionally, they are abundant in protocatechuic acid, ferulic acid, and syringic acid (Gayathry and John, 2023). These compounds are known for their potent antioxidant and anticancer properties (Gayathry and John, 2023).

The pseudostem is notably rich in amines, including serotonin and choline, along with a variety of amino acids, with tyrosine and lysine being the most abundant, as well as organic acids. Serotonin, well-known for its role in mood regulation, also supports gut motility, thereby contributing to its potential use in gut health supplements. Additionally, the lignans and coumarins found in the pseudostem contribute to its diverse range of bioactive compounds, offering further antioxidant and antimicrobial benefits (Deng et al., 2020; Padam et al., 2014; Ramírez-Bolaños et al., 2021).

The pseudostem is rich in notable compounds, including asiatic acid, oleanolic acid, maslinic acid, and various sterols and terpenes. These compounds exhibit anticholesterolemic, antioxidant, and anti-inflammatory properties, which may contribute to the prevention of metabolic disorders (Deng et al., 2020; Dikshit et al., 2016; Ramu et al., 2016) (Table 2). Specifically, asiatic acid, an active component of Indian pennywort, is recognized for its potential to promote various therapeutic benefits. Meanwhile, oleanolic acid has been widely studied for its anti-inflammatory, anticancer, and hepatoprotective properties (Deng et al., 2020; Dikshit et al., 2016; Ramu et al., 2016). Additionally, triterpenes such as cycloartenol serve as precursors in the biosynthesis of plant sterols and have been investigated for their capacity to modulate lipid metabolism, making them valuable in the development of functional foods aimed at managing cholesterol levels (Du et al., 2022).

A comprehensive analysis of dehydrated banana stems has revealed a notable concentration of essential fatty acids, specifically omega-3 and -6, when compared to other types of fatty acids (Ramírez-Bolaños et al., 2021). This composition exceeds that found in various other plant materials. Additionally, a study reported that the primary lipid components in the pulp of 'Fenjiao' bananas were glycerides and glycerophospholipids, comprising 60.33 % and 30.43 % of the total lipids, respectively (Su et al., 2024). Furthermore, it was observed that triacylglycerol levels increased significantly during the senescence stage (Su et al., 2024), highlighting the potential of this banana waste as a feedstock for biorefineries. However, it is crucial to note that the bioactivity of omega-3 fatty acids in plants cannot be directly compared to that obtained from animal sources due to biochemical variations, and the total amount is too low to be regarded as a source of essential fatty acids.

Other food-related applications of banana wastes

Banana waste is increasingly recognized for its potential in indirect food applications, due to its inherent properties. Its abundant availability makes it an excellent resource for large-scale initiatives, including wastewater treatment in the food industry, bioenergy production, and as a sustainable raw material for animal feed and biofertilizers. This ensures a consistent supply without depleting resources.

Banana waste, which is rich in fiber, minerals, proteins, water, carbohydrates, and phytochemicals, presents a promising alternative to animal feed. Numerous studies have investigated the incorporation of banana pseudostems into animal diets (Nannyonga et al., 2018). For instance, banana leftovers, including pseudostems, can replace up to 75 % of cornmeal in lamb diets without any adverse effects (Menezes et al., 2020). Another study examined the impact of including banana crop waste in the diets of ¾ Holstein × ¼ Zebu heifers, focusing on nutrient intake and digestibility, microbial protein synthesis, feeding behavior, and overall animal performance. The findings indicated that banana waste could serve as a partial substitute for sorghum silage without negatively impacting the heifers' weight gain or body development (Rigueira et al., 2021). Additionally, replacing 8 % of dietary cornmeal with whole banana meal in the practical diet of tambaqui (*Colossoma macropomum,* G. Cuvier, 1818) maintained fish growth, indicating that banana waste is an economically viable alternative in practical fish diets (Silva et al., 2020). Collectively, these studies suggest that banana waste is a potentially adequate substitute for conventional livestock feed.

A key attribute that underscores the suitability of banana waste is its rich carbon content. A LCA study on activated carbon derived from banana peel waste found it led to reduced consumption of fossil resources and lower land use intensity (Pereira et al., 2024). Furthermore, the LCA revealed significant reductions in GHG emissions contributing to the mitigation of the effects of global warming potential (GWP), human non-carcinogenic toxicity (HNCT), and soil emissions, thereby minimizing the risk of terrestrial ecotoxicity (Pereira et al., 2024). Additionally, research indicates that cellulosic ethanol produced from banana agricultural waste has the potential to lower GHG emissions, mitigate fossil fuel depletion, and sustain a positive energy balance (Guerrero and Muñoz, 2018).

Due to the vital role of carbon in numerous organic processes and products, banana waste has emerged as an excellent candidate for biochar production, outperforming other vegetable-based feedstocks (Pradhan et al., 2020). This carbon-rich biochar not only improves soil health but also promotes effective carbon sequestration. Furthermore, its high carbon content renders it valuable during fermentation processes, supporting microbial growth and metabolic activities necessary for producing industrially important metabolites, such as food enzymes (Ravindran et al., 2018). Additionally, research has shown that banana leaves serve as effective substrates for cultivating paddy straw mushrooms (*Volvariella volvacea* (Bul.) Singer) and oyster mushrooms (*Pleurotus* spp.), yielding superior results in both quantity and quality compared to rice straw (Belewu and Belewu, 2005).

Due to its abundance in cellulose, hemicellulose, and lignin, as well as its high moisture-retention potential, banana waste has been shown to function effectively as a moisture adsorbent. Numerous studies have highlighted its remarkable capacity for trapping contaminants, especially when supplemented with enhancements like nanomaterials (Liu et al., 2022; Shen et al., 2020). Research has also underscored the effectiveness of banana peels as drying agents, particularly in applications such as air drying and dehumidification. The inherent porosity of this waste, combined with its chemical composition, significantly bolsters its capacity to retain moisture (Putra et al., 2022).

The presence of a natural microbial flora in banana waste underscores its potential as an effective biofertilizer. These native microorganisms can enrich the soil with beneficial microbes that promote plant growth, enhance nutrient uptake, and help combat plant diseases (Mohd Zaini et al., 2022b). Furthermore, banana waste is rich in essential macronutrients that are beneficial for both composting and anaerobic digestion processes. For example, banana peels are rich in calcium, which supports enhanced root growth and oxygenation, magnesium for improved photosynthesis, and sulfur for strengthening roots and repelling pests. Moreover, the phosphorus found in the peels facilitates pollination and seed germination, while also promoting fruiting and flowering. Potassium, in particular, contributes significantly to overall plant health, bolstering disease resistance and fruit development (Yunus et al., 2022).

Banana waste valorization strategies

Integrated banana waste valorization encompasses a multi-stage process that converts discarded biomass into a variety of value-added products. This integrated approach not only minimizes waste and reduces environmental impact but also generates significant economic opportunities across the food, packaging, energy, and agricultural sectors. Based on established waste valorization management practices, we propose the following flow for the utilization of banana waste (Figure 3).

The process begins with the collection and sorting of various components of banana waste, including peels from processing plants, pseudostems and leaves from plantations, and discarded fruits, all of which are gathered directly on-site. This approach minimizes the transportation of wet waste, helping to reduce spoilage. During the sorting phase, contaminants such as soil and stones are meticulously removed to ensure a clean raw material for subsequent processing.

Figure 3 – Illustration of banana waste flowchart valorization strategies.

Next, pretreatment is applied to stabilize and sanitize the collected waste. This process includes thorough washing with water or a mild sanitizing solution (e.g., at a concentration of 200 mg L^{-1}) to eliminate microbes and pesticide residues. Large pseudostems are chopped into manageable pieces, while banana peels are typically blanched to deactivate enzymes, thereby reducing browning and oxidation. These measures are critical for ensuring safety, preserving nutritional quality, and achieving uniformity throughout the waste stream.

The subsequent phase, known as primary processing, focuses on reducing moisture and transforming biomass into usable intermediates. Various drying methods, including sun drying, oven drying, or dehydration, are employed to lower the moisture content and prevent spoilage. After drying, the material is milled or pulverized into fine flours and fiber powders. Alternatively, targeted extraction processes can isolate specific components, namely starch (especially from green banana peels) and cellulose fibers (notably from stems), using chemical treatments and high-shear blending for bioplastic applications. In contrast, solvent extraction methods, such as ethanol/water mixtures, are employed to recover bioactive compounds like phenolics and pectin.

During the product formulation stage, processed intermediates are converted into market-ready products. For instance, banana peel flour and pseudostem fiber are combined with conventional flour to produce high-fiber, functional foods that are enriched with antioxidants and essential nutrients. Additionally, edible films and coatings are developed from banana polysaccharides, including starch and pectin, which provide antimicrobial properties and serve as moisture barriers, thereby prolonging the shelf life of fresh produce. Furthermore, banana fibers and starches are integrated into bioplastic formulations, often in conjunction with polymers, such as Polylactic Acid (PLA), to produce environmentally friendly packaging materials.

The final products and their distribution effectively integrate these innovations into the marketplace. The end products include fully marketable functional foods, such as bread, cookies, pasta, or snack bars enriched with banana peel flour, which are high in fiber and antioxidants. Additionally, fresh produce can be enhanced with banana-based edible coatings that extend shelf life. Biodegradable packaging options include compostable plates, films, and foam packaging made from banana fibers. Moreover, banana peel extracts can be formulated as nutraceuticals or dietary supplements. Throughout this process, rigorous quality control and regulatory compliance measures ensure that all products adhere to food safety, nutritional, and environmental standards.

Commercial feasibility, technical challenges, and regulatory considerations

Banana waste valorization leverages the abundant and low-cost biomass generated during banana cultivation. Nearly 80 % of the banana plant's mass is typically discarded, which includes peels, pseudostems, leaves, and rejected fruits. This waste serves as an excellent feedstock for biorefineries and initiatives aimed at a circular economy (Nascimento et al., 2021). Converting banana waste into bioplastics presents a significant opportunity to address the growing demand for biopolymers, with global bioplastics production reaching 2.18 million tons in 2023, and packaging accounting for roughly 43 % of this usage (Ghasemlou et al., 2024). Within the bio-packaging sector, research has demonstrated successful production of biodegradable films utilizing cellulose and starch sourced from banana peels (Hoque and Janaswamy, 2024).

Similarly, edible coatings and natural preservatives derived from banana waste hold significant market potential. For instance, sprays made from banana peel extract have been shown to extend the shelf life of fruits by 2-3 days (Rahman et al., 2020). Additionally, extracts from banana inflorescence have proven effective as natural antioxidant additives in meats, successfully preventing lipid oxidation at low inclusion rates (Zou et al., 2022). These applications illustrate a pathway from waste to value-added products, including biodegradable packaging, shelf-life-extending coatings, and functional food ingredients. This trend is particularly relevant as both consumers and regulators increasingly emphasize the use of sustainable materials and clean-label preservatives.

Despite its potential, the valorization of banana waste encounters several technical and economic challenges. The highly perishable and heterogeneous nature of banana biomass, characterized by its high moisture content and rapid spoilage, complicates storage, transportation, and processing (Castillo et al., 2023; Segura-Badilla et al., 2022). Achieving consistent quality is difficult due to variations in banana varieties, maturity (green vs. ripe peels), and farming practices, all of which influence the functional properties of the final products, such as fiber and polyphenol content (Segura-Badilla et al., 2022).

In bioplastic applications, achieving the requisite mechanical and barrier properties without relying on synthetic additives poses a significant challenge. While banana fiber and starch-based films often require the inclusion of plasticizers or cross-linkers to improve flexibility, these additives may compromise biodegradability (Negrete-Bolagay and Guerrero, 2024). In food formulations, the dark color and mild bitterness associated with banana peel polyphenols can restrict their incorporation levels in delicately flavored products. However, studies indicate that sensory performance remains acceptable with up to 10 % substitution (Segura-Badilla et al., 2022). Scaling up production presents another major obstacle, as many processes are still confined to pilot-scale operations. The high capital costs linked todrying, milling, and extraction, combined with the necessity for a reliable collection network and stabilization methods - such as converting peels into shelf-stable flours or pellets - pose significant economic challenges (Negrete-Bolagay and Guerrero, 2024). Furthermore, banana biomass competes with alternative uses, including animal feed, compost, or textile fibers, and must demonstrate clear cost or performance advantages over established alternatives (Zou et al., 2022).

Ensuring that products derived from banana waste adhere to safety and quality standards is crucial for commercialization (Mohd Zaini et al., 2022a). When utilized in food applications, banana waste needs to be processed to eliminate contaminants, such as heavy metals and pesticide residues. For instance, methods such as washing and blanching have been effective in reducing microbial loads while preserving nutritional quality, thereby ensuring that products like banana peel flour comply with regulatory requirements (Segura-Badilla et al., 2022). Regulatory agencies may categorize banana waste derivatives as novel food ingredients, which demands comprehensive safety evaluations and strict adherence to Good Manufacturing Practices (GMP). In packaging applications, bioplastic films produced from banana waste must comply with food contact material regulations to obtain compostability certifications (e.g., EN 13432 or ASTM D6400) (Negrete-Bolagay and Guerrero, 2024). Additionally, clear labeling is essential to inform consumers about the sustainable and upcycled nature of these products, mitigating any concerns regarding their origin. As regulatory frameworks evolve, further research and standardization will be necessary to ensure that banana waste products are both safe and market-ready.

Final remarks

Banana waste, which includes peels, pseudostems, leaves, and inflorescences, is rich in a variety of bioactive compounds and nutrients, presenting promising opportunities for applications in functional foods, nutraceuticals, and sustainable packaging. By valorizing these underutilized resources, we can achieve significant environmental benefits, such as waste reduction and decreased GHG emissions, while also creating new economic opportunities within a circular economy framework. Despite these encouraging prospects, several research gaps remain. Future studies should focus on standardizing extraction and quantification methods for bioactive compounds, optimizing scalable processing technologies, and conducting comprehensive life cycle and economic feasibility analyses. Additionally, further investigation into regulatory requirements and consumer acceptance is essential to ensure the development of safe, effective, and market-ready applications. Addressing these challenges will be critical in transforming laboratory insights into practical solutions that fulfill the potential of banana waste for sustainable development.

Acknowledgments

The authors thank Universiti Malaya Research Excellence Grant with reference to UMREG017-2023 and University Putra Malaysia University Research Driven Program (UPM UDRP) for the financial support.

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Conflict of interest

The authors declare that there is no conflict of interest.

Data availability statement

The contents underlying the research text are included in the manuscript.

Declaration of use of AI Technologies

The authors used generative AI and AI-assisted technologies (ChatGPT 4 and Grammarly) in the writing process to improve the readability and language of the text.

References

Abd Rahim MH. 2025. Palm milk: a nutritious, sustainable and versatile plant-based alternative to coconut milk. Food Reviews International 3: 1-6. https://doi.org/10.1080/87559129.2025.2473018

Abdel-Naeem HHS, Elshebrawy HA, Imre K, Morar A, Herman V, Pașcalău R, et al. 2022. Antioxidant and antibacterial effect of fruit peel powders in chicken patties. Foods 11: 301. https://doi.org/10.3390/foods11030301

Aboul-Enein AM, Salama ZA, Gaafar AA, Aly HF, Abou Elella F, Ahmed HA. 2016. Identification of phenolic compounds from banana peel (*Musa paradaisica* L.) as antioxidant and antimicrobial agents. Journal of Chemical and Pharmaceutical Research 8: 46-55.

Afzal O, Dalhat MH, Altamimi ASA, Rasool R, Alzarea SI, Almalki WH, et al. 2022. Green tea catechins attenuate neurodegenerative diseases and cognitive deficits. Molecules 27: 7604. https://doi.org/10.3390/molecules27217604

Ahsan M, Ashraf H, Iahtisham-Ul-Haq, Liaquat A, Nayik GA, Ramniwas S, et al. 2024. Exploring pectin from ripe and unripe banana peel: a novel functional fat replacer in muffins. Food Chemistry: X 23: 101539. https://doi.org/10.1016/j.fochx.2024.101539

Al-Mqbali LRA, Hossain MA. 2019. Cytotoxic and antimicrobial potential of different varieties of ripe banana used traditionally to treat ulcers. Toxicology Reports 6: 1086-1090. https://doi.org/10.1016/j.toxrep.2019.10.003

Alzate Acevedo S, Díaz Carrillo ÁJ, Flórez-López E, Grande-Tovar CD. 2021. Recovery of banana waste-loss from production and processing: a contribution to a circular economy. Molecules 26: 5282. https://doi.org/10.3390/molecules26175282

Amornlerdpison D, Choommongkol V, Narkprasom K, Yimyam S. 2021. Bioactive compounds and antioxidant properties of banana inflorescence in a beverage for maternal breastfeeding. Applied Sciences 11: 343. https://doi.org/10.3390/app11010343

Amutha K, Sudha A, Saravanan D. 2022. Characterization of natural fibers extracted from banana inflorescence bracts. Journal of Natural Fibers 19: 872-881. https://doi.org/10.1080/15440478.2020.1764437

Arumugam S, Pugazhenthi G, Selvaraj S. 2023. Investigations on mechanical properties of processed banana leaves for sustainable food packaging applications. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.02.256

Aziz NAA, Ho L-H, Azahari B, Bhat R, Cheng L-H, Ibrahim MNM. 2011. Chemical and functional properties of the native banana (*Musa acuminata* × *balbisiana Colla* cv. Awak) pseudo-stem and pseudo-stem tender core flours. Food Chemistry 128: 748-753. https://doi.org/10.1016/j.foodchem.2011.03.100

Azman EM, Yusof N, Chatzifragkou A, Charalampopoulos D. 2022. Stability enhancement of anthocyanins from blackcurrant (*Ribes nigrum* L.) pomace through intermolecular copigmentation. Molecules 27: 5489. https://doi.org/10.3390/molecules27175489

Balasubramanian P. 2022. Going bananas! The science and tradition of eating on banana leaves. Science Meet Food. Available at: https://sciencemeetsfood.org/banana-leaves [Accessed Jan 2, 2025]

Bashmil YM, Ali A, Amrit BK, Dunshea FR, Suleria HAR. 2021. Screening and characterization of phenolic compounds from Australian grown bananas and their antioxidant capacity. Antioxidants 10: 1521. https://doi.org/10.3390/antiox10101521

Begum YA, Deka SC. 2019. Chemical profiling and functional properties of dietary fibre rich inner and outer bracts of culinary banana flower. Journal of Food Science and Technology 56: 5298-5308. https://doi.org/10.1007/s13197-019-04000-4

Belewu MA, Belewu KY. 2005. Cultivation of mushroom (*Volvariella volvacea*) on banana leaves. African Journal of Biotechnology 4: 1401-1403.

Bhavani M, Morya S, Saxena D, Awuchi CG. 2023. Bioactive, antioxidant, industrial, and nutraceutical applications of banana peel. International Journal of Food Properties 26: 1277-1289. https://doi.org/10.1080/10942912.2023.2209701

Buzby J. 2023. Federal Interagency Collaboration to Reduce Food Loss and Waste. USDA, Washington, DC, USA. Available at: https://www.usda.gov/foodlossandwaste/interagency [Accessed Jan 2, 2025]

Cabrera D, Baykara H, Riofrio A, Cornejo M, Cáceres J. 2023. Preparation, characterization, and life cycle assessment of banana rachis-recycled high-density polyethylene composites. Scientific Reports 13: 16534. https://doi.org/10.1038/s41598-023-42613-0

Castillo M, Guzman MJ, Aberilla JM. 2023. Environmental sustainability assessment of banana waste utilization into food packaging and liquid fertilizer. Sustainable Production and Consumption 37: 356-368. https://doi.org/10.1016/j.spc.2023.03.012

Chakraborty R, Sabruna S, Roy R, Majumdar S, Roy S. 2021. Banana pseudostem substitution in wheat flour biscuits enriches the nutritional and antioxidative properties with considerable acceptability. SN Applied Sciences 3: 75. https://doi.org/10.1007/s42452-020-03988-1

Chiang S-H, Yang K-M, Lai Y-C, Chen C-W. 2021. Evaluation of the in vitro biological activities of banana flower and bract extracts and their bioactive compounds. International Journal of Food Properties 24: 1-16. https://doi.org/10.1080/10942912.2020.1856134

Chockchaisawasdee S, Stathopoulos CE. 2022. Functional oligosaccharides derived from fruit-and-vegetable by-products and wastes. Horticulturae 8: 911. https://doi.org/10.3390/horticulturae8100911

Corona MAG, Patiño MB, Flores MJP, Ruiz LAM, Martinez BMB, Baez DA. 2015. An integrated analysis of the *Musa paradisiaca* peel, using UHPLC-ESI, FT IR and confocal microscopy techniques. Annals of Chromatography and Separation Techniques 1: 1005. https://doi.org/10.36876/acst.10

Correa M, Bombardelli MCM, Fontana PD, Bovo F, Messias-Reason IJ, Maurer JBB, et al. 2017. Bioactivity of extracts of *Musa paradisiaca* L. obtained with compressed propane and supercritical CO_2. Journal of Supercritical Fluids 122: 63-69. https://doi.org/10.1016/j.supflu.2016.12.004

Deng G, Sheng O, Bi F, Li C, Dou T, Dong T, et al. 2020. Metabolic profiling in banana pseudo-stem reveals a diverse set of bioactive compounds with potential nutritional and industrial applications. Phyton 89: 1101-1130. https://doi.org/10.32604/phyton.2020.010970

Dikshit P, Tyagi MK, Shukla K, Gambhir JK, Shukla R. 2016. Antihypercholesterolemic and antioxidant effect of sterol-rich methanol extract of stem of *Musa sapientum* (banana) in cholesterol-fed wistar rats. Journal of Food Science and Technology 53: 1690-1697. https://doi.org/10.1007/s13197-015-2096-5

Du Y, Fu X, Chu Y, Wu P, Liu Y, Ma L, et al. 2022. Biosynthesis and the roles of plant sterols in development and stress responses. International Journal of Molecular Sciences 23: 2332. https://doi.org/10.3390/ijms23042332

Fingolo CE, Braga JMA, Vieira ACM, Moura MRL, Kaplan MAC. 2012. The natural impact of banana inflorescences (*Musa acuminata*) on human nutrition. Anais da Academia Brasileira de Ciências 84: 891-898. https://doi.org/10.1590/S0001-37652012005000067

Food and Agriculture Organization [FAO]. 2024. Banana Market Review 2023. FAO, Rome, Italy. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/1085e3ed-0f37-4e7d-848d-cdfe203be158/content [Accessed Jan 2, 2025]

Food and Agriculture Organization [FAO]. 2025. Banana Facts and Figures. FAO, Rome, Italy. Available at: https://www.fao.org/economic/est/est-commodities/oilcrops/bananas/bananafacts/en [Accessed Jan 2, 2025]

Fung SM, Razali Z, Somasundram C. 2021. Involvement of phenolic compounds and their composition in the defense response of *Fusarium oxysporum*-infected Berangan banana plants. Sains Malaysiana 50: 23-33. https://doi.org/10.17576/jsm-2021-5001-03

Gayathry KS, John JA. 2023. Phenolic profile, antioxidant, and hypoglycaemic potential of pseudostem and inflorescence extracts of three banana cultivars. Biomass Conversion and Biorefinery 15: 2387-2395. https://doi.org/10.1007/s13399-023-04970-8

Gengan G, Mohd ZNS, Saari N, Meor HAS, Jaafar AH, Hasan H, et al. 2024. Nutritional and therapeutic benefits of coconut milk and its potential as a plant-based functional yogurt alternative: a review. Food Science and Human Wellness 14: 9250004. https://doi.org/10.26599/FSHW.2024.9250004

Gengatharan A, Abd Rahim MH. 2023. The application of clove extracts as a potential functional component in active food packaging materials and model food systems: a mini-review. Applied Food Research 3: 100283. https://doi.org/10.1016/j.afres.2023.100283

Ghasemlou M, Barrow CJ, Adhikari B. 2024. The future of bioplastics in food packaging: an industrial perspective. Food Packaging Shelf Life 43: 101279. https://doi.org/10.1016/j.fpsl.2024.101279

Ghosh M, Ghosh P. 2020. Storage study of grapes (*Vitis vinifera*) using the nanocomposite biodegradable film from banana pseudostem. Journal of Food Processing and Preservation 44: 12. https://doi.org/10.1111/jfpp.14917

Guerrero AB, Muñoz E. 2018. Life cycle assessment of second generation ethanol derived from banana agricultural waste: environmental impacts and energy balance. Journal of Cleaner Production 174: 710-717. https://doi.org/10.1016/j.jclepro.2017.10.298

Ha Thi D, Cao Thi H, Hue Van NL, Tran Y DT, Hoang H. 2024. Comprehensive analysis of phytochemicals and biological potential of banana leaf *Musa acuminata* AAA. SSRN (preprint). http://dx.doi.org/10.2139/ssrn.4964287

Hajar-Azhari S, Wan-Mohtar WAAQI, Ab Kadir S, Abd Rahim MH, Saari N. 2018. Evaluation of a Malaysian soy sauce *koji* strain *Aspergillus oryzae* NSK for γ-aminobutyric acid (GABA) production using different native sugars. Food Science and Biotechnology 27: 479-488. https://doi.org/10.1007/s10068-017-0289-6

Hikal WM, Said-Al Ahl HAH, Bratovcic A, Tkachenko KG, Sharifi-Rad J, Kačániová M, et al. 2022. Banana peels: a waste treasure for human being. Evidence-Based Complementary and Alternative Medicine 2022: 7616452. https://doi.org/10.1155/2022/7616452

Hoque M, Janaswamy S. 2024. Biodegradable packaging films from banana peel fiber. Sustainable Chemistry and Pharmacy 37: 101400. https://doi.org/10.1016/j.scp.2023.101400

Izzati N, Mohamed Nawawi N, Ijod G, Abas F, Ramli N, Mohd Adzahan N, et al. 2023. Influence of different drying methods on anthocyanins composition and antioxidant activities of mangosteen (*Garcinia mangostana* L.) pericarps and LC-MS analysis of the active extract. Foods 12: 2351. https://doi.org/10.3390/foods12122351

Jamaluddin F, Noranizan MA, Azman EM, Mohamad A, Yusof NL, Sulaiman A. 2022. A review of clean-label approaches to chilli paste processing. International Journal of Food Science & Technology 57: 763-773. https://doi.org/10.1111/ijfs.15293

Kalwar PR, Kolte SS, Thaker K. 2021. Identification of progesterone in the banana inflorescence of *Musa paradisiaca* L. species by using HPTLC and GC-MS techniques. Analytical Chemistry Letters 11: 39-54. https://doi.org/10.1080/22297928.2021.1876574

Kappel VD, Cazarolli LH, Pereira DF, Postal BG, Madoglio FA, Buss ZS, et al. 2013. Beneficial effects of banana leaves (*Musa x paradisiaca*) on glucose homeostasis: multiple sites of action. Revista Brasileira de Farmacognosia 23: 706-715. https://doi.org/10.1590/S0102-695X2013005000062

Khamsucharit P, Laohaphatanalert K, Gavinlertvatana P, Sriroth K, Sangseethong K. 2018. Characterization of pectin extracted from banana peels of different varieties. Food Science and Biotechnology 27: 623-629. https://doi.org/10.1007/s10068-017-0302-0

Kora AJ. 2019. Leaves as dining plates, food wraps, and food packing material: importance of renewable resources in Indian culture. Bulletin of the National Research Centre 43: 205. https://doi.org/10.1186/s42269-019-0231-6

Kraithong S, Issara U. 2021. A strategic review on plant by-product from banana harvesting: a potentially bio-based ingredient for approaching novel food and agro-industry sustainability. Journal of the Saudi Society of Agricultural Sciences 20: 530-543. https://doi.org/10.1016/j.jssas.2021.06.004