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Review Article

Fermented Fruits in Asia: Fermentation Process, Microbes, and Health Benefits

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ABSTRACT

Human health is significantly influenced by the food we eat. Fruits are one of the most important plant-based foods, offering numerous health benefits. Increasing evidence suggests that some naturally occurring compounds in fruits are responsible for biological effects on health. Fruit is defined as the seed-bearing part of a plant, and by this definition, many fruits are small, inedible, and often toxic. However, the fruits we commonly consume today are widely cultivated around the world, though their origins vary. The history of how different fruits, native to various regions, reached Asia is unique, often facilitated by birds, humans, or other means. This review focuses on ten specific fruits: noni, dragon fruit, rambutan, mango, mangosteen, durian, jackfruit, guava, papaya, and coconut. Fermentation is one of the oldest processes in biotechnology and can occur due to factors such as the availability of starter cultures and suitable environmental conditions. Fruits are fermented to produce products such as fermented juice, pulp, or paste. Fermentation is also valued for increasing the shelf life and enhancing the aroma and taste of foods. Lactic acid bacteria are the most common type of microbes found in fermented foods, with *Lactobacillus plantarum* being one of the most prevalent species in fermented fruit samples. The probiotics present in fermented foods are believed to provide various health benefits. This review explores the unique characteristics of different fruits in Asia, their fermentation process, the microbes present in the fermented fruit sample, and the associated health benefits.

Keywords: Fruits, Asia, Fermentation, Microbes, Human Health.

Introduction

Human health is significantly influenced by the food we eat.[1] Fruits are one of the most important plant-based foods, offering numerous health benefits.[2] They are essential natural resources of ample nutrients, such as sugars, organic acids, and secondary metabolites.[3] Additionally, they offer bioactive phytochemicals, including flavonoids and phenolic compounds, which have been linked to numerous health advantages.[2] Regular fruit consumption appears to help prevent a wide range of chronic diseases.[4] Demand for fruits and vegetables has drastically increased due to changing dietary habits and a growing population.[5] Increasing evidence suggests that some naturally occurring compounds in fruits are responsible for beneficial biological effects on health.[6]

Fermentation of food is one of the oldest processes in biotechnology.[7] The potential benefits of fermented food include improved flavour, texture, shelf life, and health benefits. Fermented foods are widely accepted in developing countries due to their ability to maintain quality under ambient conditions, their safety, and their traditional acceptability.[8] Various food products can be produced by selecting different raw materials, such as fruits, vegetables, milk, and using specific starter cultures and fermentation conditions. The most used starter culture in food fermentation is Lactic Acid Bacteria (LAB), which accounts for the majority of the volume and value in commercial starter cultures.[9]

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The primary function of these cultures in food fermentation is to convert carbohydrates into desirable metabolites such as alcohol, acetic acid, lactic acid, or carbon dioxide (CO_2). Alcohol and organic acids are natural preservatives, which are also appreciated in fermented products.[9] Fermented foods have been associated with various health benefits, including the prevention and management of metabolic disorders, cardiovascular disease, cognitive improvement, immune enhancement, and so on.[10]

This review highlights ten fruits that are significantly found in Asia, including noni (*Morinda citrifolia*)[11], dragon fruit (*Hylocereus polyrhizus*)[12], rambutan (*Nephelium lappaceum* L)[13], mango (*Magnifera indica* L.)[14], mangosteen (*Garcinia mangostana* Linn.)[15], durian (*Durio zibethinus* Murr)[16], jackfruit (*Artocarpus heterophyllus* Lam)[17], guava (*Psidium gujava* L.)[18], papaya (*Carica papaya* L.)[19], and coconut (*Cocos nucifera* L.)[20]. These fruits are noteworthy in both traditional and modern contexts across Asia due to their well-known nutritional and medicinal properties. They were selected for their high concentration of key nutrients, including vitamins, minerals, antioxidants, and bioactive compounds, and offer various health benefits such as anti-inflammatory, antibacterial, anticancer, and antioxidant properties. A significant number of these fruits are also fermented, often involving the use of lactic acid bacteria (LAB), which improves their flavor, texture, shelf life, and nutritional bioavailability, hence augmenting their nutraceutical qualities. This review aims to provide an overview of the current state of knowledge about the ten most commonly available fruits in Asia, including fermentation methods, the microbes involved in the process, and the health benefits of consuming these fermented fruits.

Ten Most Common Fruits Present In Asia

The botanical definition of a fruit refers broadly to the seed-bearing part of a plant, and by this definition, many fruits are small, inedible, and often toxic. Nuts are similarly the seeds inside fruits. There are 'n' number of fruits present in Asia, and for this review, 10 have been selected: noni, dragon fruit, rambutan, mango, mangosteen, durian, jackfruit, guava, papaya, and coconut. These fruits either originated in or are widely grown in Asia. According to Morton, noni can spread along ocean currents and has become established along seacoasts around the world. It may have originated in Southeast Asia, although some claimed it originated in Northern Australia, which is home to other related species. Noni is one of the most widespread fruits in the Pacific, having spread to India, the Seychelles, and the Caribbean. This plant is significant for its fruit, medicinal properties, and the red dye obtained from its roots.[21]

The dragon fruit, an eye-catching fruit native to Central America, is now widely available in marketplaces across the region, with Vietnam being a major producer.[22] Rambutan, originally from Malaysia and Indonesia, is distributed throughout Southeast Asia. *Mangifera indica*, believed to have originated in India or Burma, spread to Southeast Asia over the past two millennia before being introduced to the Pacific in the post-European era. Both mangosteen and durian are widespread in mainland and island Southeast Asia, though mangosteen originated in Indochina, whereas durian is native to Malaya and Indonesia. Jackfruit and guava, originating from India and Mexico respectively, are now distributed worldwide.[21]

Spaniards are known to have carried papaya seeds, which are native to Central America, to the Philippines around 1550. The papaya then spread to the rest of Southeast Asia and to India.[22] Coconut is believed to have originated in the New World, as its closest botanical cousins are found there; however, its exact origin is still debated, with claims suggesting it could have from multiple sources.[21] The ten fruits discussed in this review either originated in or are widely planted in various Asian countries and are well-known for different reasons.

Morinda citrifolia

Noni fruit (Figure 1(i)) comes from a plant scientifically named *Morinda citrifolia*. It is also known by several other names, including great morinda, Indian mulberry, beach mulberry, and cheese fruit. Belonging to the Rubiaceae family, the plant is distributed along worldwide coastlines.[21] The ripened fruit has a strong pungent smell, a bitter taste, and contains numerous seeds. Due to these unfavourable characteristics, the fruit is preferably changed into fermented juice, which is done naturally without the addition of external agents or by adding sugar and a starter culture.[23] The fruit and leaves of the plant are important food resources and are commonly used in various cooking processes.[24] *M. citrifolia* is a significant traditional Polynesian medicinal plant, heavily promoted for its use in treating conditions such as arthritis, burns, circulatory weakness, diabetes, cancer, skin inflammation, and wounds. A wide variety of drinks, powders, and cosmetic products are also made from noni fruit.[25]

Hylocereus polyrhizus

Dragon fruit (*Hylocereus polyrhizus*) (Figure 1(ii)), also called pitaya, originated in Mexico and South America but is now widely grown in Southeast Asia, including Malaysia and Vietnam. The fruit consists primarily of glucose and fructose as its major sugar components. It is rich in vitamin C, soluble fibers, and potassium, contains a low amount of lipids, and is slightly acidic [pH-4.3 to 4.7].[27] Dragon fruit belongs to the Cactaceae family. There are two types of dragon fruit, which are differentiated by the color of the flesh−either white or red.[28] The fruit is oval-shaped and contains tiny black seeds. Pitahaya, dragon pearl fruit, night-blooming cereus, strawberry pear, and Cinderella plant are some other names for this fruit.[29] Fermentation of pitaya is a natural process in which small pieces of the fruit are added to a glass jar and rested for 7 to 21 days. Red dragon fruit is useful for various preparations, such as fruit juice, fermented drinks, ice cream, jams, candies, and yogurt.[27] The consumption of pitaya is known to help with cardiovascular health and has antioxidant and anti-inflammatory properties.[29]

Nephelium lappaceum L.

Nephelium lappaceum L., also known as rambutan (Figure 1(iii)), is mostly found in Indonesia, Thailand, Malaysia, and Vietnam.[31] The fruit is ellipsoidal in shape, with white, juicy pulp and oval seeds enclosed in a distinctive yellow to crimson skin covered with soft spines. The various by-products obtained from the fruit, such as the peel and seed, are usually discarded; however, studies have shown that these by-products can be used as functional ingredients in food and health applications.[32] The fruit is a significant commercial crop in Asia and is typically eaten fresh, canned, or processed into juice, jam, jelly, marmalade, spread, chips, or packed with a piece of pineapple and canned in syrup. The fermentation of rambutan is done naturally, without the addition of other ingredients. The fruit pulp is placed in a perforated plastic container and left to rest for eight days. According to studies, fermenting rambutan can transform the fruit into various products, which eventually reduces wastage.[33] The volatile compounds present in *Nephelium lappaceum L.* are responsible for its antioxidant and antimicrobial properties.[32]

Mangifera indica L.

Mango (*Mangifera indica L.*) (Figure 1(iv)) originated in India or Burma and has spread throughout Southeast Asia.[21] It is one of the best-known horticultural fruits and a member of the Anacardiaceae family.[35] There are a total of 30 species of fruiting trees belonging to the Anacardiaceae family. The mango is a well-known large drupe, but it comes in a wide variety of sizes and shapes. When ripe, it has thick yellow pulp, a solitary seed, and a thick yellowish-red peel. The seed is solitary, ovoid or oblong, and protected by a fibrous endocarp that is rigid and compacted. The pulp contains vitamins A and C, β-carotene, and xanthophylls.[36] Mango juice is inoculated with a suitable LAB culture and incubated at 37°C for 24 hours to obtain fermented mango juice.[37] *Mangifera indica L.* has been an important Ayurvedic herb in the medicinal system for over 4000 years. Consuming ripe mango fruit is invigorating, and different parts of the mango tree provide various health benefits.[36]

Garcinia mangostana Linn.

Mangosteen (Figure 1(v)) or *Garcinia mangostana Linn*., is a popular fruit cultivated in Southeast Asian countries, including Thailand. This fruit has a pleasant aroma and is soft, juicy, and sweet, with a mildly acidic flavour. It is therefore widely known and often referred to as the "queen of fruits" and a medicinal herb in Thailand. Suitable LAB cultures are inoculated into juice prepared by pressing the pulp of the fruit and incubated at 30°C for 72 hours to obtain a fermented mangosteen sample. Different parts of the mangosteen contain phytochemicals such as xanthones, phenolic compounds, anthocyanins, and procyanidins. In particular, α-xanthones and γ-mangostin are major bioactive ingredients with anti-proliferative, pro-apoptotic, anti-cancer, anti-diabetic, antimicrobial, and anti-inflammatory properties, as well as protective effects against on various human organs.[39]

Durio zibethinus Murr.

Durian (*Durio zibethinus Murr.*) (Figure 1(vi)) is one of the most popular fruits in Southeast Asia and is widely cultivated in Malaysia and Indonesia.[21] It is also called the “king of fruits” due to its sweet, custard-like flesh and unique, intense aroma. The taste of durian is often described as a blend of avocado and mango. The fruit has a round or oblong shape, a flat seed, bright yellow flesh, a creamy texture, a bittersweet flavour, and a potent aroma, and it is regarded as one of the richest and best-tasting fruit.[31] For those unfamiliar with it, the fruit’s highly pungent smell can be overpowering, while for those who are accustomed to it, it is delightful. Due to the volatile esters and sulphur-containing compounds present, the aroma of durian is often compared to that of onions or a blend of aged cheese. There are 30 species of durian around the world, of which 10 are considered edible by cultivators. It is also one of the most in-demand fruits among consumers these days, as it is seasonal.[42] Tempoyak is a fermented durian paste made by adding salt to overripe durian. Tempoyak is also known to have antimicrobial properties.[43]

Artocarpus heterophyllus Lam

Jackfruit (*Artocarpus heterophyllus Lam*) (Figure 1(vii)) is predominantly grown in Southeast Asian countries such as Thailand, Indonesia, and Malaysia.[45] The fruit is oval in shape and turns yellowish-green when ripe. It typically weighs between 16 and 20 kilograms and is highly nutritious. It has a juicy texture and a sweet taste. The most popular variety among Malaysian consumers is the

Tekam Yellow variety. For prolonged usage, jackfruit pulp is often dried, powdered, and stored in suitable bags.[46] The fruit is commonly consumed fresh or processed into jams, jellies, and pickles. Due to its high sugar content, jackfruit juice is also recommended as a useful substrate for fermentation, particularly in the production of wine. Jackfruit pulp suspension is prepared by inoculating it with yeast and acetic acid bacteria and incubating it at 30°C for a week to obtain fermented jackfruit pulp suspension.[46,47] The flesh of the jackfruit offers great potential for creating various fermented foods that are rich in bioactive compounds and possess anti-cancer properties.[45]

Psidium gujava L.

Guava (*Psidium guajava L.*) (Figure 1(viii)), also known as the "Apple of the Tropics", is widely grown in tropical and subtropical regions around the world. India is one of the largest producers of guava, along with China, Thailand, Pakistan, Mexico, Indonesia, Brazil, and Bangladesh, which also contribute notable amounts. The fruit, consumed both fresh and in processed forms such as juices, confections, and derivatives, is rich in vitamin C and contains expressive quantities of sugar, vitamins A and B, iron, phosphorus, and calcium.[49] Depending on the variety, guava may have green or yellow skin with white, pink, or red flesh. It has a pleasant aroma and a sweet-sour flavour. Additionally, guava is high in dietary fibre, pectin, minerals, and fermentable sugars such as fructose, glucose, and sucrose. For fermentation, guava pulp is mixed with water and sugar, inoculated with the desired culture, and incubated at 37°C under static conditions.[50] Fermented guava exhibits enhanced antioxidant and anti-inflammatory effects.[51] *Psidium guajava L.* is also considered an economically important fruit, as it contains numerous biologically active substances.[52]

Carica papaya L.

Papaya, or *Carica papaya L.* (Figure 1(ix)), is widely cultivated around the world for its taste and nutritional value.[54] It is grown extensively in places such as Brazil, Hawaii, Florida, South Africa, India, and Australia. Christopher Columbus once referred to papaya as "the fruit of the angels" or "a fruit of long life".[55] It is one of those plants that has been grown for centuries, with a notably rapid growth mechanism. Initially, the fruit is hard and inedible, but as it ripens, it softens and becomes edible, developing a pleasant aroma. However, if the fruit matures unchecked, it can result in pulp softening, changes in skin and pulp colour, and the development of strong odours. These changes are related to increased ethylene production, which contributes to postharvest losses.[56] The fermentation of papaya is typically carried out by lactic acid bacteria (LAB) in a laboratory setting. In this process, papaya puree, combined with other ingredients, is inoculated with LAB strains and incubated under static conditions for 48 hours at 37°C. Papaya is known to have numerous health benefits, including antidiabetic, anticancer, anti-inflammatory, and antioxidant properties. It is also beneficial for addressing skin issues.[55]

Cocos nucifera L.

Coconuts (Figure 1(x)), scientifically known as *Cocos nucifera L.*, are widely planted in Southeast Asian countries and are now spread worldwide. Coconut water is a liquid endosperm that begins to form in small amounts by the third month of maturation, peaks at eight months, and then steadily diminishes as the nut matures. It is a clear, colourless liquid with a pH ranging from 4.2 to 6.0, and it is pleasant, naturally flavored, and faintly acidic. Coconut water contains trace levels of carbohydrates, such as glucose, fructose, sucrose, and sorbitol, as well as essential amino acids like lysine, histidine, tyrosine, and tryptophan. It also contains organic acids such as tartaric, citric, and malic acids. The mesocarp (flesh) of the coconut is white in color and is used for various purposes, including cooking, oil extraction, and milk preparation. Fermentation of coconut water is performed by inoculating it with a suitable probiotic LAB strain and incubating it at 37°C for two days. This process converts coconut water into a probiotic beverage, valued for its nutritional properties and significant health benefits. Regular consumption of tender coconut water has been shown to offer numerous medicinal benefits for humans.[58]

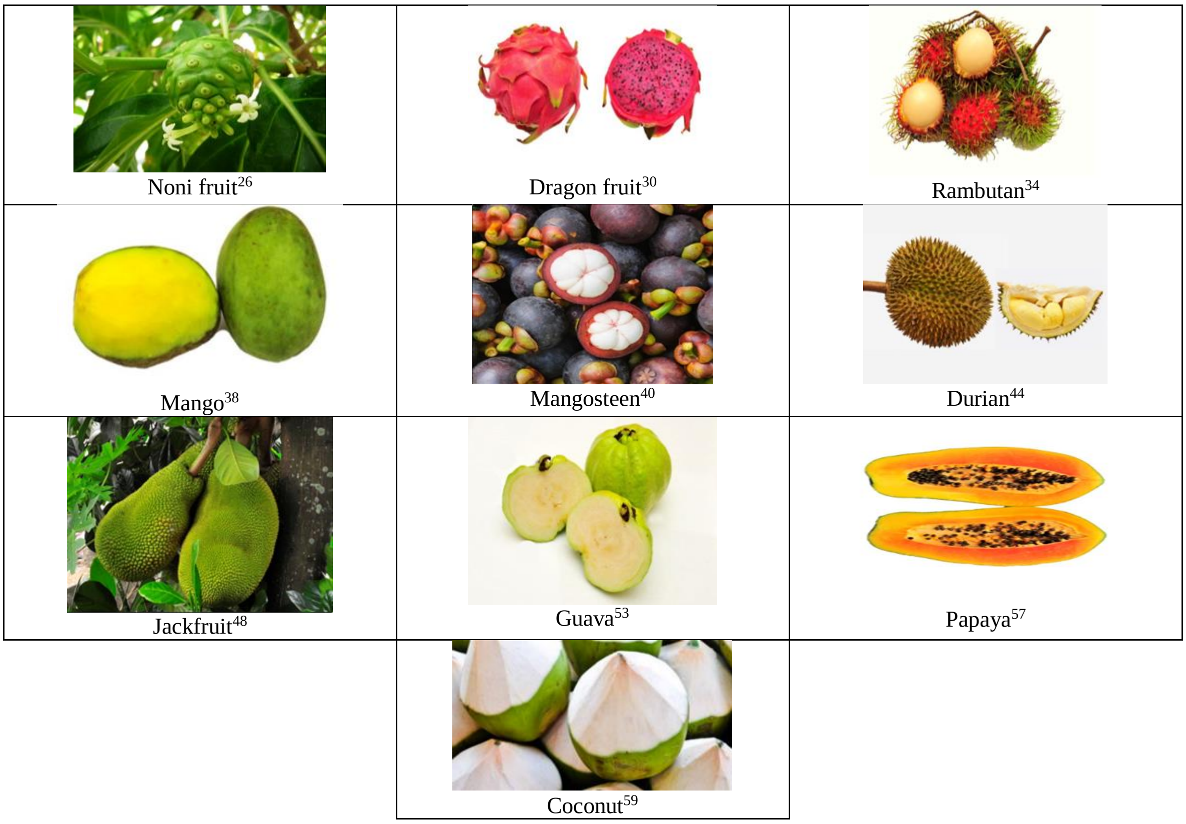

Figure 1: Image of common fruits found in Asia

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Fermentation Methods

Fermentation is a sustainable bio-preservative technique that enhances the nutritional and gustatory qualities of food.[37] It can be carried out using various methods, depending on external factors such as the type of starter culture, additional materials, and suitable conditions. This review focuses on common and straightforward methods used to ferment fruits, either naturally or in a laboratory setting, to prepare fermented fruit juice, pulp, or paste, which can further be used for consumption or research purposes.

Morinda citrifolia

The fermentation of noni juice was done by its intrinsic enzymes and natural mutualistic microorganisms. The noni fruit was cut into pieces to fit into a 2000 mL container, and 500 mL of water was added. The fruit pieces were left to ferment for 6-10 weeks at room temperature. At the end of the fermentation period, 400 mL of the fermented noni stock was transferred to a 1000 mL container. The 400 mL stock was then filtered using Whatman filter paper and vacuum filtration to eliminate debris and fruit particles from the stock solution (Figure 2).[60]

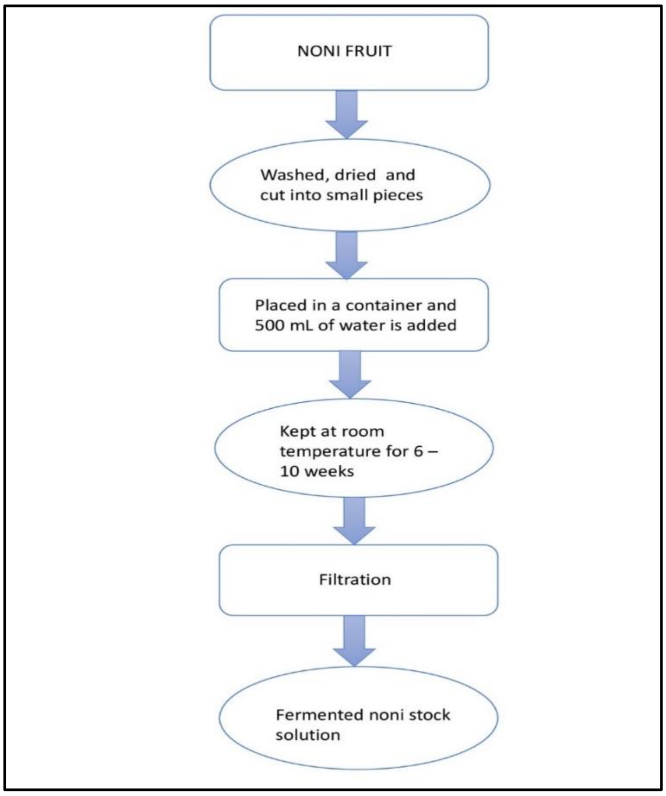

Figure 2: Flow chart of noni fermentation

Hylocereus polyrhizus

To prepare a fermented dragon fruit juice sample, red dragon fruit was either harvested or purchased from the nearest market, washed, cut into small pieces, and added to a glass jar. The samples were prepared with and without the addition of sugar (10% [w/v]) and fermented for 7 and 21 days, respectively, without inoculating any other microorganisms. After fermentation, the juice was collected and stored at 4°C in a sterile Schott bottle. To prevent contamination from environmental microbes, the sample preparation process was carried out aseptically (Figure 3).[27]

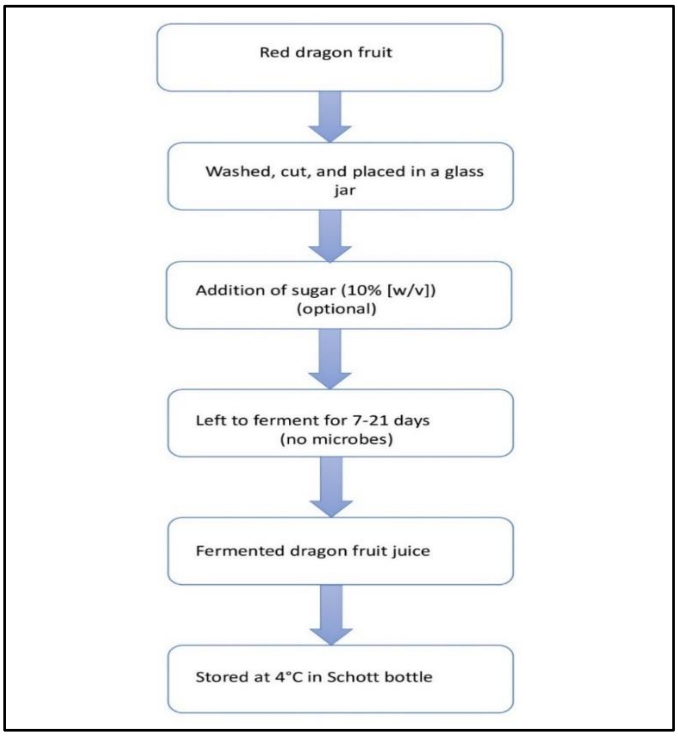

Figure 3: Flow chart of dragon fruit fermentation process

Nephelium lappaceum L

Before starting the fermentation process, 7 kg of rambutan fruit was cleaned and peeled. The peeled fruit was then placed in a perforated open plastic container for fermentation. Each perforation, made using a soldering iron, was spaced 1 cm apart. To catch the sweating created during fermentation, a non-perforated plastic container was positioned beneath each perforated one. Before moving the setup into an incubator cupboard (30±2°C) for eight days of fermentation, the rambutan fruits were completely covered with tap-water-washed banana leaves to create an anaerobic environment (Figure 4).[33]

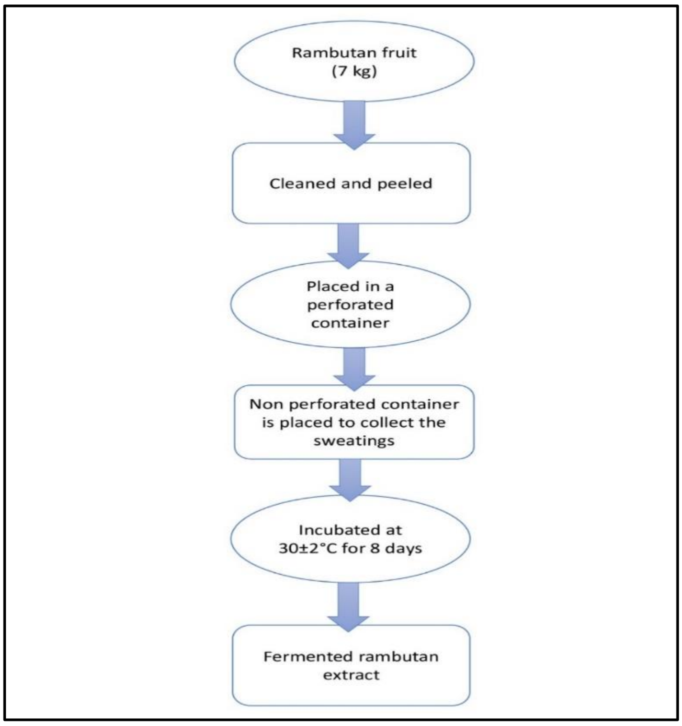

Figure 4: Flow chart of rambutan fermentation

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Mangifera indica L.

Fresh mangoes were purchased from the local market, washed, peeled, cut into small pieces, and blended using a mixer without adding water. The mango juice was then homogenized at 10,000 rpm for 15 minutes. A sterile 100 mL flask containing 50 mL of the prepared mango juice was pasteurized for five minutes in a water bath at 80 °C (internal temperature), followed by 100°C (external temperature) while being continuously shaken. A quick ice-water bath (0 °C) cooling process was used to bring the pasteurized juice to room temperature.

Lactic acid bacteria strains (*Levilactobacillus brevis*, *Lacticaseibacillus casei*, *Lacticaseibacillus rhamnosus*, *Lactiplantibacillus plantarum subsp. plantarum, and Pediococcus. pentosaceus*) were bought, cultured, and activated. Pasteurized mango juice was inoculated with monoculture-washed bacterial cells (1% v/v), then incubated at 30°C or 37°C (optimal growth temperature) for 24 hours to obtain mango juice fermented by *Levilactobacillus brevis*, *Lacticaseibacillus casei*, *Lacticaseibacillus rhamnosus*, *Lactiplantibacillus plantarum subsp. plantarum, and Pediococcus. pentosaceus*. Pasteurized mango juice without the addition of LAB was incubated under the same conditions (30°C, 24 h) and used as a control. To end the fermentation, the juices were held at 4°C for another 12 hours before further use (Figure 5).[37]

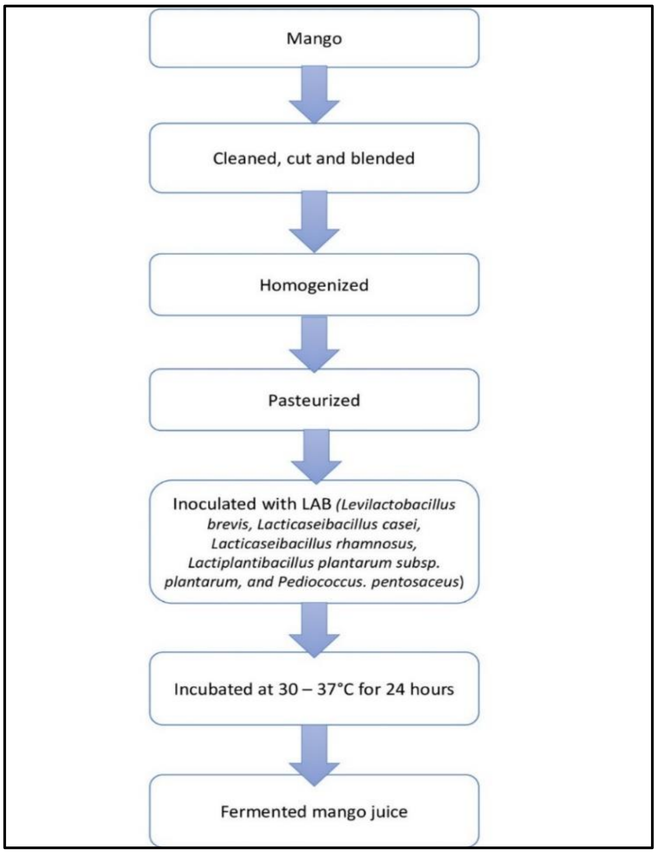


Figure 5: Flow chart of mango fermentation method

Garcinia mangostana Linn.

Mature mangosteen was selected, peeled, and washed in distilled water. The aril (pulp) was separated from the pericarp. Mangosteen juice was prepared from the aril using a hydraulic press. The prepared juice was then mixed with distilled water in a 30:70 ratio (Mangosteen juice: distilled water). The total soluble solids of the mixture were 7 ° Brix, which was adjusted to 13° Brix by adding sucrose and 0.3 % (w/v) salt. Probiotic LAB strains, such as *L. casei, L. fermentum,* and *L. plantarum,* were activated in De Man–Rogosa–Sharpe (MRS) broth, inoculated into the mangosteen juice, and incubated at 30°C for 72 hours under static conditions (Figure 6).[39]

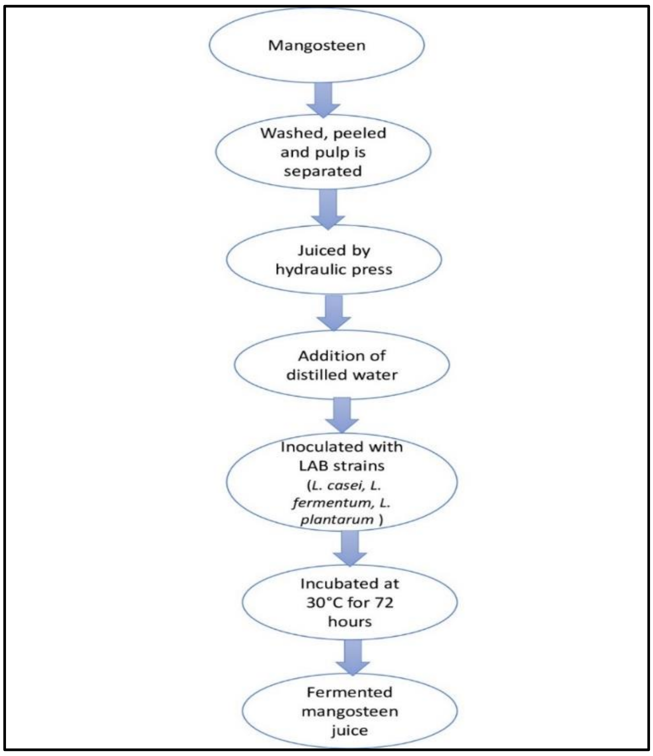


Figure 6: Flow chart of fermentation of mangosteen

Durio zibethinus Murr.

Tempoyak is a fermented durian paste made by adding salt to overripe durian. This process typically occurs at home. Fermentation of durian can take place with or without the addition of salt. The overripe durian was selected, and the seeds were removed and cut into small pieces. Salt was then added, and the mixture was placed in an airtight container. Salt plays a crucial role in promoting lactic acid fermentation and helps prevent contamination by microflora other than LAB. Anaerobic fermentation by LAB took place over 3-8 days at room temperature, between 28-34°C. This is a spontaneous fermentation process. LAB counts were high when 1% of salt was used, but the final product was more acidic and had a higher salt concentration. Based on sensory properties, 2% salt is preferred. A higher salt concentration leads to a longer shelf life compared to a lower concentration (Figure 7).[43]

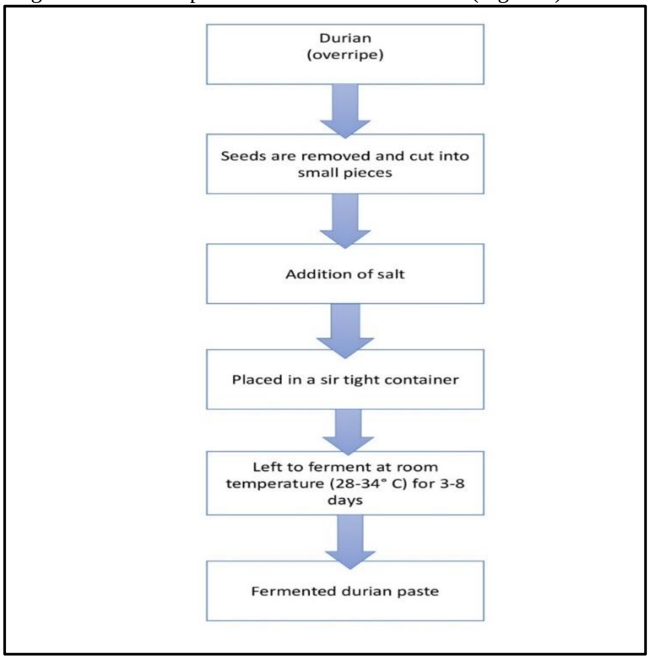


Figure 7: Flow chart of durian fermentation

Artocarpus heterophyllus Lam

The ripened jackfruit was selected, and the pulp was separated from the seed, which was then washed thoroughly in filtered water. The clean jackfruit pulp was minced into smaller chunks and dried in the oven at 45°C to produce pulp granules. As a growth medium to produce fermented jackfruit pulp, a jackfruit pulp suspension at a concentration of 5% (w/v) was prepared. This suspension was inoculated with yeast (*Dekkera sp.*) and acetic acid bacteria (*Komagataiebacter sp.*) and left to ferment at 30°C for a week (7 days). After a week of fermentation, the supernatant was collected by centrifugation at 11,200 g for 10 minutes to remove microbes and substrate. The final extract, named fermented jackfruit pulp, was obtained from the substrate of jackfruit pulp (Figure 8).[46,47]

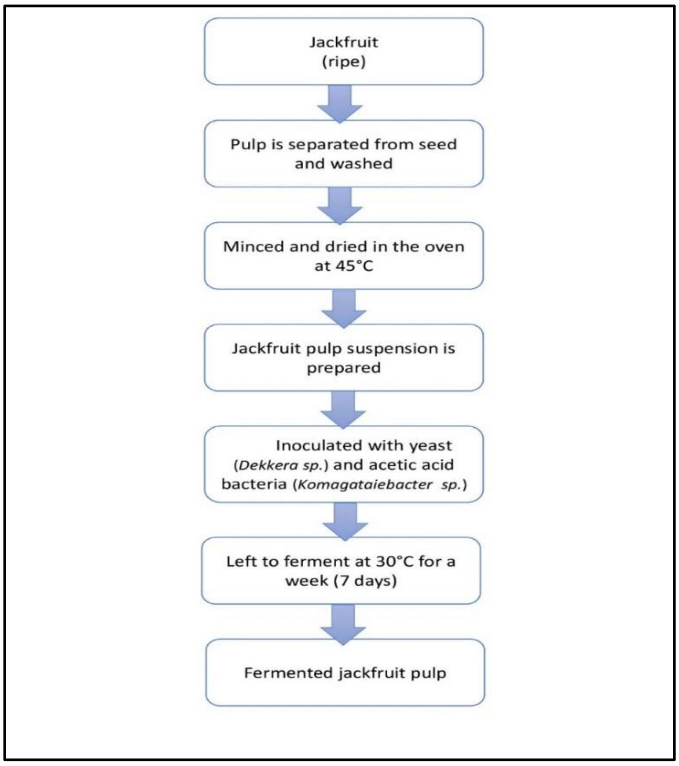


Figure 8: Flow chart of jackfruit fermentation

Psidium gujava L.

White-fleshed mature guava fruits weighing between 0.2 and 0.3 kg each were collected. The seeds were manually removed after the fruits were chopped into small pieces using a knife and then cleaned with tap water. The cut pieces were processed for five minutes at speed setting 1 in an electric blender until they were reduced to a pulp. To extract the juice, the pulp was strained through muslin fabric with 0.7-mm pores. The pulp was kept at 20°C until needed. 200 g (fresh weight) of pulp was produced for every 1,000 g of fresh guava weight. In a stainless-steel pot, 700 g of drinking water, 20 g of sugar, and 300 g of guava pulp were combined. The components were mixed and then pasteurized by gradually heating to 85°C while stirring occasionally, holding at this temperature for 15 minutes by removing the pot from the heater as needed, and then cooling to room temperature. The pH was brought down to 6.0 before inoculation using a sterile ammonia solution (0.5% v/v). The starter culture *Lactobacillus plantarum WU-P19* was bought and prepared. The guava pulp mixture (5 mL of L. *plantarum WU-P19* pure culture) prepared earlier was mixed with the bacterial inoculum in 2-L sterile stainless-steel containers. The mixture was incubated at 37°C for fermentation under static conditions. The duration of fermentation was determined by the time required for the pH of the fermenting material to decline to 3.2–3.5 (Figure 9).[50]

Carica papaya L.

To prepare a total of 200 g of fermented sample, 45% papaya puree, 45% distilled water, 5% edible glucose, and 5% skim milk powder (10-fold diluted) were added to a conical flask. The mixture was then heated to 90°C for 10 minutes, sterilized, and cooled in a water bath. Each LAB strain, *L. acidophilus and L. plantarum,* was inoculated at 5% of the mass ratio of the fermentation broth. The mixture was then incubated under static conditions for 48 hours at 37° C. Samples were stored at 80°C. The fermentation process was repeated three times (Figure 10).[54]

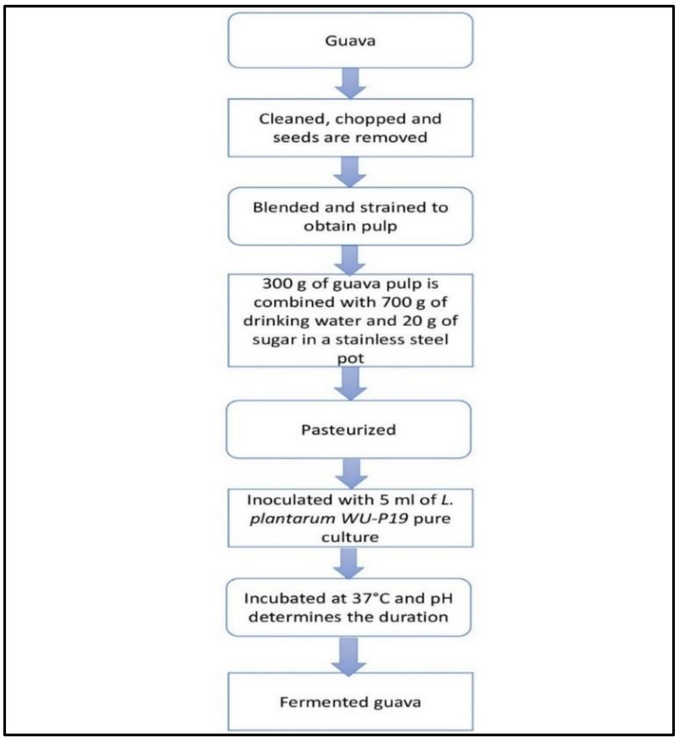


Figure 9: Flow chart of Guava fruit fermentation

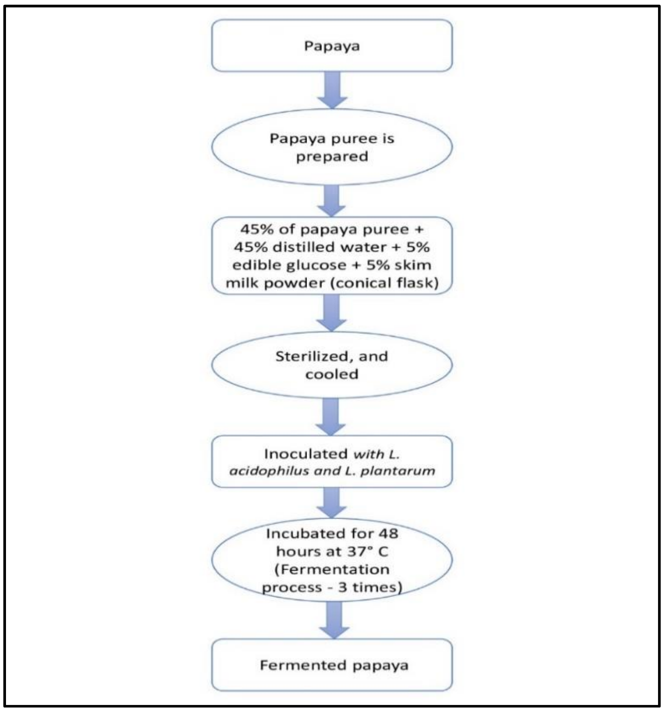


Figure 10: Flow chart of the fermentation process of papaya

Cocos nucifera L.

The two probiotic strains, *L. plantarum* and *L. helveticus*, were taken and propagated separately in sterile MRS broth, incubated for 24 hrs at 37°C, and then stored at 4°C for later use. These strains were subjected to optimization studies to determine the preferable growth temperature, which was found to be 35°C. The strains are then freeze-dried to produce dried powders of probiotic bacterial cultures. During this process, bacterial cells are frozen and dried to preserve their viability and probiotic potential. The cultures are activated for use in fermentation.

Fresh, green tender coconuts purchased from the local market were perforated with a sterile knife to collect the tender coconut water. Tender coconut water (TCW) was first cultured in sterile Erlenmeyer flasks holding 250 mL with 100 mL of the sample. The flasks with TCW were inoculated with LAB cultures. Batch fermentations were carried out in duplicate for two days at a constant temperature of 37°C. After two days of incubation, samples were taken aseptically by gently rotating the conical flasks and used as needed (Figure 11)[58].

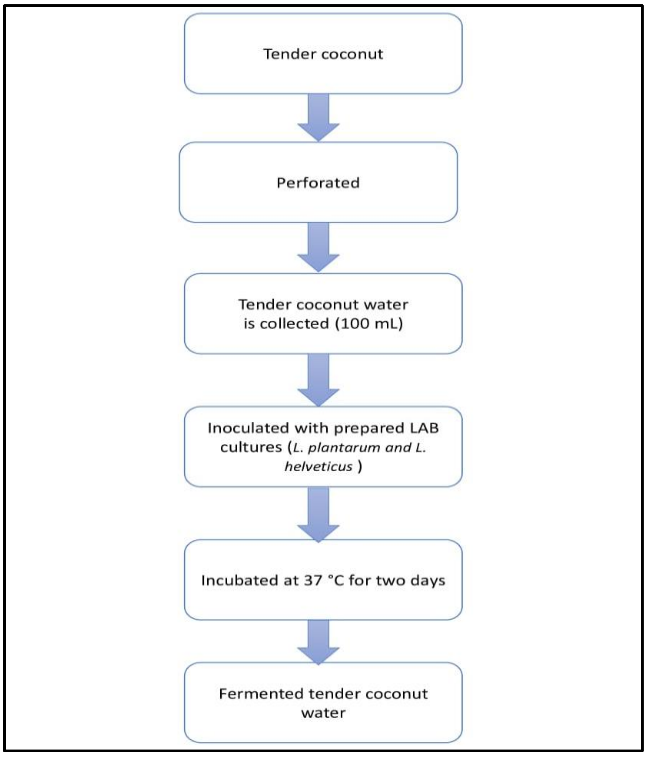


Figure 11: Flow chart of tender coconut fermentation

Microbes Isolated from Fermented Fruits

Lactic acid bacteria (LAB) are gram-positive bacteria that rely solely or primarily on carbohydrates for carbon. They are typically cocci or rods with a high tolerance for low pH. Although there are over 60 genera of LAB, the most common ones found in food fermentation include *Lactobacillus, Lactococcus, Leuconostoc, Pediococcus, Streptococcus, Enterococcus, Weissella,* and others. Recently, it was proposed to combine the families *Lactobacillaceae* and *Leuconostocaceae* into a single family, *Lactobacillaceae*. Additionally, *Lactobacillus* has been reclassified into 25 genera. LAB should exhibit several significant metabolic characteristics as fermentation strains, including the ability to produce acid and aroma, hydrolyze protein, produce viscous exopolysaccharides, and effectively inhibit bacteria.[61] Microbes present in fermented fruits are listed in Table 1. These microbes are isolated from naturally fermented fruits. In other cases, microbes are purchased and cultured to induce fermentation, and the growth of the specific organism is measured. In this way, the microbes present in each fermented fruit are assessed. *Lactobacillus plantarum* is one of the most common species in fermented fruit samples studied. Other organisms present in the fermented fruits reviewed include *Enterobacteriaceae, Acetobacteraceae, Enterococcus faecalis, E. durans, Levilactobacillus brevis, Lacticaseibacillus casei, Lactiplanti bacillus plantarum subsp. Plantarum, Lacticaseibacillus rhamnosus, Pediococcus pentosaceus, L. fermentum, Fructobacillus durionis, L. acidophilus, Lactobacillus helveticus*. Fermented samples of mango, mangosteen, durian, guava, papaya, and coconut showed growth of *Lactobacillus plantarum* (Figure 12). *Lactobacillus plantarum* is a rod-shaped, gram-positive lactic acid bacterium that thrives at temperatures ranging from 15-45˚C, with an optimal temperature of 37˚C. It requires pH levels as low as 3.2 but prefers a range of 6.2-6.6. *L. plantarum* is a facultative heterofermentative organism that ferments sugar to produce lactic acid, ethanol, acetic acid, and carbon dioxide under specific conditions and selective substrates. This bacterium can switch between heterofermentative and homofermentative metabolism depending on its carbon supply and can thrive in the human gastrointestinal tract because of its high acid and bile salt tolerance. Researchers and food scientists are interested in *L. plantarum* because of its safety as a probiotic. In conclusion, among the most common fruits found throughout Asia that were selected for this review, *Lactobacillus plantarum* is the most prevalent species, present in six out of ten samples.

Figure 12: Microscopic image of *Lactobacillus plantarum*[62]

Health Benefits of Fruits found in Asia

Eating fruits is well known to be extremely beneficial to one's health, a fact supported by numerous scientific studies worldwide. World Health Organization (WHO) and the Food and Agriculture Organization (FAO) recommend a specific amount of vegetables and fruits in daily meals to prevent chronic pathologies such as hypertension, coronary heart disease, and the risk of stroke. Lactic acid bacteria (LAB), present in all fermented foods, are known to positively modify the intestinal microbiota and prevent the colonization of enteric pathogens. They also improve digestive functions, enhance the immune system, reduce the risk of colorectal cancer, control serum cholesterol levels, and eliminate unrequired antinutritional compounds present in food. Lactic acid bacteria offer numerous health benefits, as illustrated in Figure 13.[68]

Each fruit selected for this review has its own significance for health.

Noni is well known globally as a health supplement.[69] A recent human trial studying the potential health benefits of noni juice concludes that it has greater antioxidant activity and offers various other benefits. These include protection against toxicities caused by tobacco smoke, normalization of blood lipids, increased physical endurance, higher immune activity, weight management, DNA protection, control of systemic inflammation and blood pressure, maintenance of bone health in women, and improved gum health.[24] This fruit contains iridoids, a phytochemical recognized for its anti-aging properties.[14] The structure of major phytochemical compounds in noni fruits is shown in Table 2. Deacetylasperulosidic acid (DAA), asperulosidic acid, and rutin (Table 2) are among the major and most common phytochemicals found in noni fruit juice.[24,23] DAA has been shown to increase enzymatic antioxidant activity in Wistar rats when fed for seven days, validating the antioxidant potential of noni juice.[14] Asperulosidic acid and rutin isolated from Hawaiian noni fruit juice have demonstrated potential anti-inflammatory action.[13] Additionally, another animal study related to the consumption of fermented noni juice shows evidence supporting its anti-diabetic properties.[70]

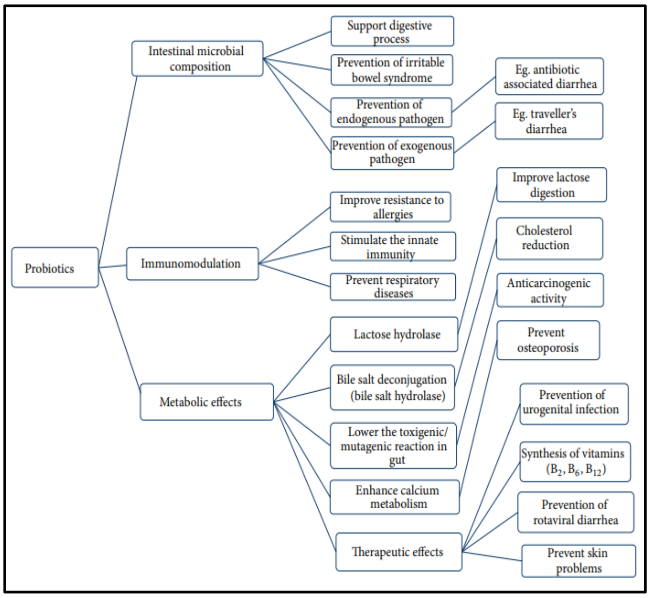


Figure 13: Beneficial effects of probiotics[68]

Pitaya has been shown to offer potential health benefits, including antioxidant, anti-inflammatory, antilipemic, anti-diabetic, anti-bacterial, anti-fungal, and anti-cancer effects. The consumption of dragon fruit may help mitigate oxidative stress and support anti-inflammatory processes. It has also been demonstrated to reduce diabetes risk and improve cardiovascular health.[29] *Hylocereus spp.* is a significant source of betalains, which are hydrophilic, nitrogen-containing pigments with betalamic acid as the chromophore (as shown in Table 3). These pigments can conjugate with cyclo-3,4-dihydroxyphenylalanine (DOPA) to produce betacyanins, red-violet pigments (Table 3).[72] Studies indicate that betalains may help reduce of risk factors associated with certain cancers, cardiovascular and cerebrovascular diseases, as well as liver and kidney damage.[73] Additionally, pitaya peels are known to contain bioactive phytochemicals, particularly betacyanins, which can be used to make functional foods or extend the shelf life of food products due to their antioxidant properties.[72]

Nephelium lappaceum L. has demonstrated antibacterial effects against certain multidrug-resistant bacterial pathogens.[75] Phenolic extracts naturally present in rambutan by-products are being developed into nutraceuticals for healthcare and as preservatives in the food industry, influencing both antioxidant and antimicrobial properties.[72] Rambutan seeds are also a promising source of antioxidants.[76] In vitro, methanolic extracts of rambutan peel, containing primary phenolic compounds such as geraniin, ellagic acid, quercetin, rutin, and corilagin (Table 4), have demonstrated inhibitory activity against Gram-positive (*S. aureus* and *L. monocytogenes*) and Gram-negative bacteria (*E. coli*, *V. parahaemolyticus*, *V. anguillarum*, *P. aeruginosa*, and *S. enteritidis*), and yeast (*C. albicans*), proving their strong antimicrobial effects.[76]

Table 1: Microbes present in fermented fruits

Common name	Scientific name	Region	Family	Microbes	Reference
Noni	*Morinda citrifolia*	Tropical and subtropical	Rubiaecea	*Acetobacter fabarum, Acetobacter syzygii, Acetobacter pasteurianus, Acetobacter tropicalis, Acetobacter lambici,* and *Gluconobacter japonicus.*	25, 63
Dragon fruit	*Hylocereus polyrhizus*	Tropical	Cactaceae	*Enterococcus faecalis, E. durans*	64, 28, 27
Rambutan	*Nephelium lappaceum L*	Subtropical and tropical	Sapindaceae	-	32
Mango	*Mangifera indica L.*	Tropical	Anacardiaceae	*Levilactobacillus brevis, Lacticaseibacillus casei, Lactiplantibacillus plantarum subsp. Plantarum, Lacticaseibacillus rhamnosus, Pediococcus pentosaceus.*	35,37
Mangosteen	*Garcinia mangostana Linn*	Tropical	Clusiaceae	*L. casei, L. fermentum, L. plantarum*	39, 21, 65
Durian	*Durio zibethinus Murr.*	tropical	Bombacaceae	*Lactobacillus plantarum, Fructobacillus durionis*	21, 43
Jackfruit	*Artocarpus heterophyllus Lam*	Tropical	Moraceae	*L. casei*	66, 45
Guava	*Psidium gujava L.*	Tropical and subtropical	Myrtaceae	*Lactobacillus plantarum*	49,50
Papaya	*Carica papaya L.*	Tropical and subtropical	Caricaceae	*L. acidophilus* and *L. plantarum*	54
Coconut	*Cocos nucifera L.*	Tropical and subtropical	Arecaceae (Palmae)	*Lactobacillus plantarum* and *Lactobacillus helveticus*	58, 67

Table 2: Structure of major phytochemicals of noni fruit juice

Compounds	Structure	Reference

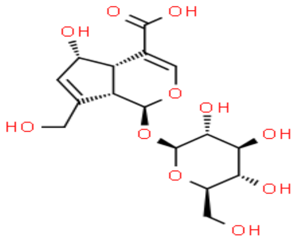
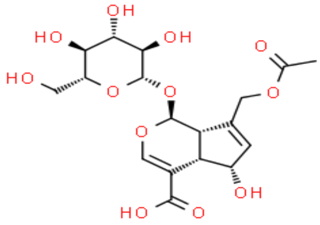
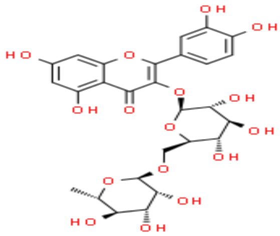
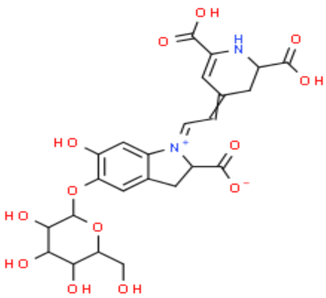
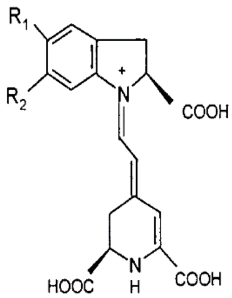
Deacetylasperulosidic acid (DAA)		71
Asperulosidic acid		71
Rutin		71

Table 3: Structure of betalains and betacyannins (major phytochemicals of dragon fruit)

Compounds	Structure	Reference
Betalains		71
Betacyannins		74

Mango possesses antidiabetic, antioxidant, antiviral, cardiotonic, hypotensive, and anti-inflammatory properties. Numerous other effects have also been examined, including hypolipidemic, antimicrobial, hepatoprotective, and gastroprotective properties. Additionally, it exhibits antibacterial, antifungal, anthelmintic, antiparasitic, antitumor, anti-HIV, anti-bone resorption, antispasmodic, antipyretic, antidiarrheal, and immunomodulatory properties.[36] Quercetin and its related glycosides are the major phytochemicals present in the pulp of mango, with quercetin 3-galactoside, quercetin 3-glucoside, quercetin 3-arabinoside and quercetin aglycone (Table 5) being the most common. Quercetin is also reported to be responsible for significant antioxidant activity.[78] Carotenoids are one other major bioactive phytochemical present in *Mangifera indica*. Mango by-products, which are high in phenolics and carotenoids, are recognized for their great potential in preventing non-communicable diseases, inflammation, and cancer.[78]

Studies on mangosteen have shown the anti-tumorigenic and anti-inflammatory activities of xanthones.[79] The pericarp of mangosteen has also been shown to possess high antioxidant, antibacterial, and anticancer properties.[65,80] Mangosteen's principal bioactive component is xanthones. Due to its wide range of biological and pharmacological properties, α-mangostin, the main xanthone derivative extracted from mangosteen, has garnered significant interest in the field of medicinal plant research (Table 6).[81] α-Mangostin exhibits strong antibacterial properties against *C. acnes* and is also known for its anti-malarial, anti-parasitic, anti-inflammatory, and anti-apoptotic properties.[81]

Table 4: Structure of major phytochemicals of *Nephelium lappaceum L.*

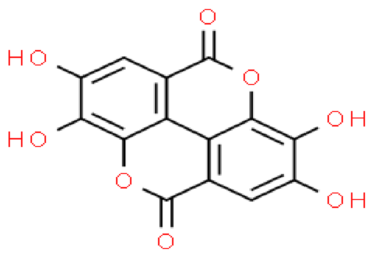
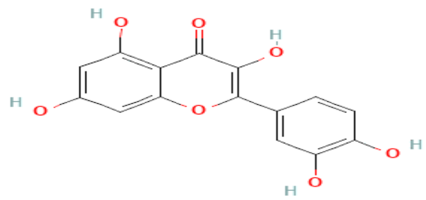
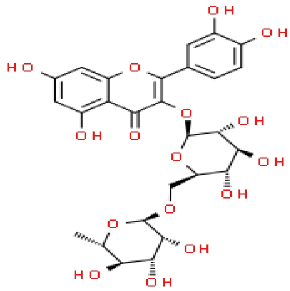
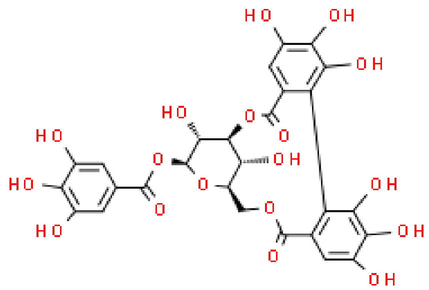
Compounds	Structure	Reference
Ellagic acid		71
Quercetin		77
Rutin		71
Corilagin		71

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Table 5: Major phytochemical structures of *Mangifera indica*

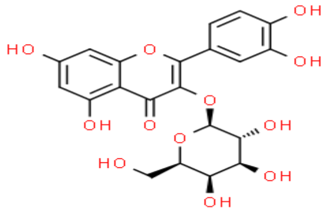
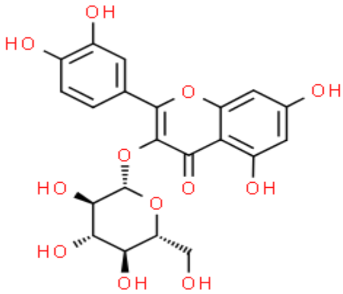
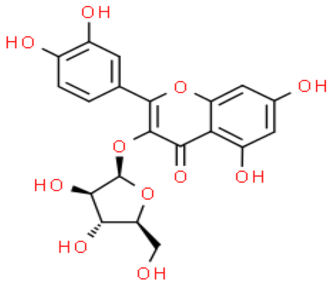
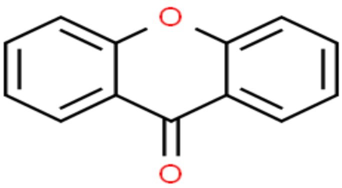
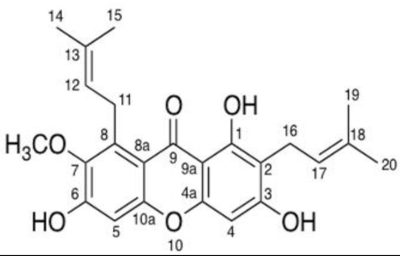
Compounds	Structure	Reference
Quercetin 3-galactoside		71
Quercetin 3-glucoside		71
Quercetin 3-arabinoside		71

Table 6: Major phytochemical structures of mangosteen

Compounds	Structure	Reference
Xanthone		71
α-mangostin		82

The fermented durian paste, "tempoyak", has bioactive properties such as antimicrobial, anti-mutagenic, and immunostimulatory effects, and it also possesses probiotic potential.[43] Quercetin, caffeic acid, and apigenin (Table 7) are some of the major phytochemical compounds detected in ripened and over-ripened durian. Durian fruit contains high levels of caffeic acid and quercetin, both of which are powerful antioxidants.[83] Quercetin is also one the most active flavonoids in the human diet. The presence of high antioxidant activity, flavonoids, and other bioactive compounds in mature durian leads to its highest antiproliferative activity in cancer cells. Durian extract is also known for its remarkable antiproliferative and anticancer properties.[83]
Traditional medicine has utilized jackfruit flesh, leaves, and bark for a variety of therapeutic properties, including antibacterial, antifungal,

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anti-inflammatory, wound-healing, and hypoglycaemic effects. Due to jackfruit's functional qualities–such as antioxidant and anticancer capabilities, as well as its ability to reduce vascular illnesses and skin disorders–the food industry has recently shown significant interest in developing jackfruit-based products, including wafers, chips, seed flour, and peel. Jackfruit pulp-added yoghurt has shown increased protein digestibility (two-fold), and higher antibacterial activity compared to regular yoghurt.[45] A study has shown that fermented jackfruit leaf beverage consumption has an anti-diabetic effect.[84] Polyphenolic substances found in jackfruit include gallic, ferulic, and tannic acids, as well as flavonoids such as catechin, rutin, and myricetin (Table 8).[85] Another study reported that the antifungal activity of polyphenols (gallic acid, catechin, and quercetin 3-galactoside) inhibited the growth of the pathogen *B. cinerea*. All the compounds mentioned above are also responsible for the antioxidant activity of jackfruit.[85]

Table 7: Structures of major phytochemicals present in durian

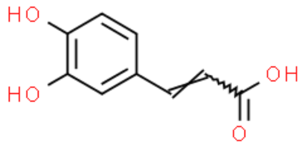
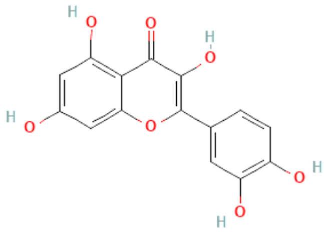
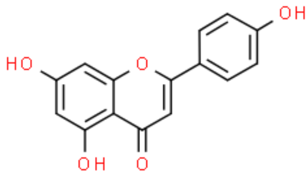
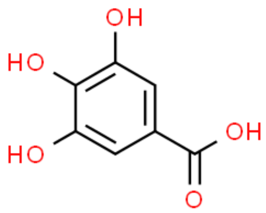
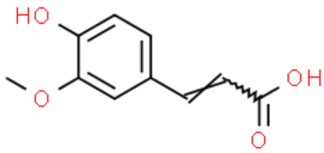
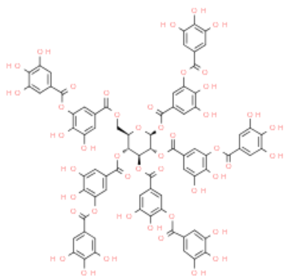
Compounds	Structure	Reference
Caffeic acid		71
Quercetin		77
Apigenin		71

Table 8: Structures of major phytochemicals present in *Artocarpus heterophyllus Lam*

Compounds	Structure	Reference
Gallic acid		71
Ferulic acid		71
Tannic acid		71

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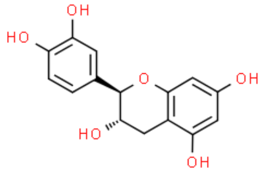
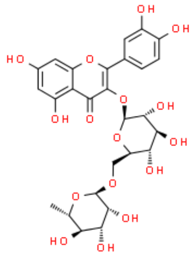
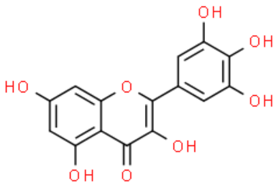
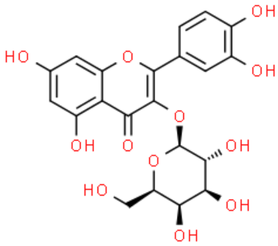
Catechin		71
Rutin		71
Myricetin		71
Quercetin 3-galactoside		71

Fermented guava has been shown to have health-promoting properties, including higher antioxidant and anti-inflammatory effects.[51] The leaves of fermented guava are shown to have antidiabetic properties[86], in addition to the fruit, other parts of the plant are incredibly useful in various ways. A study on the extraction of polyphenolic compounds from guava leaves revealed the presence of quercetin, the most active and potent antioxidants.[77] 4,5-Diepipsidial A, Apigenin, Guajadial B (Table 9) are prominent bioactive molecules isolated from guava, all of which have anticancer potential. These compounds are active against prostrate, melanoma, and liver cancer, respectively.[88] Additionally, other noteworthy compounds found in guava leaves include catechin, kaempferol, avicularin, and guavinosides B and C (Table 9), which have various positive effects on human health, such as anti-inflammatory, antibacterial, and anticancer activity.[87] Therefore, guava leaves are a significant source of polyphenolic chemicals and have the potential to be used as nutraceuticals.

Regular consumption of fermented papaya juice helps control the aging process and prevents various diseases. Papaya leaves are also known to have anti-hyperglycemic and hypolipidemic effects. A recent study has shown that papaya leaf extract lowers glucose levels and promotes weight loss in diabetic rats.[55] Papain, one of the most common phytochemicals in papaya, is a useful digestive aid that facilitates the digestion of proteins (Table 10).[89] Carpaine, an alkaloid found in papaya leaves, acts as a cardiac depressant, amoebicide, and diuretic. It helps with blood coagulation, proper heart and nervous system function, and appropriate muscular action (Table 10).[89] Papaya has also been studied for its antioxidant, anti-diabetic, anti-inflammatory, and anticancer effects.[89]

Various products obtained from the coconut fruit are known to have different health benefits. Coconut water (CW) has (+)-catechin and (-)-epicatechin (Table 11), which are compounds known for their antimicrobial, antioxidant, and anticancer properties. Fresh CW contains cytokinin, a plant growth hormone that may help human skin cells delay the onset of aging symptoms. Research suggests that CW possesses antioxidant, antibacterial, anticancer, antidiabetic, anti-atherosclerotic, cardio-protective, anti-thrombotic, hypolipidemic, anti-cholecystitis, anti-viral, anti-fungal, antiprotozoal, immune-stimulatory, hepatoprotective, and hormone-like properties.[58]

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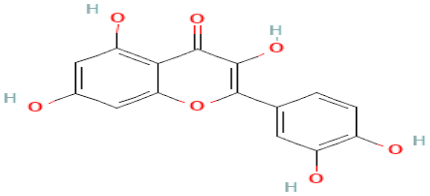
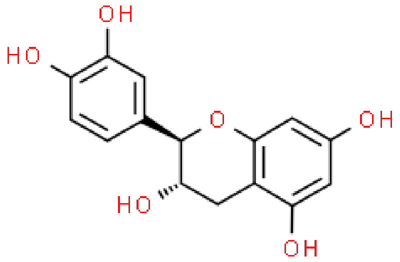
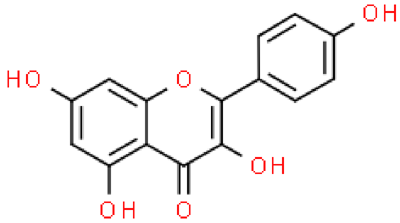
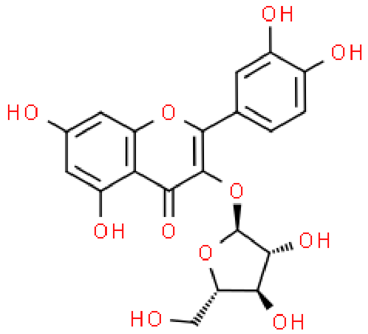
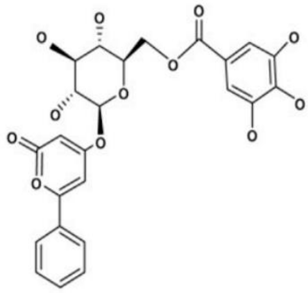
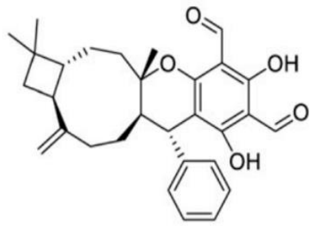
Table 9: Structures of major phytochemicals present in *Psidium guajava.*

Compounds	Structure	Reference
Quercetin		77
Catechin		71
Kaempferol		71
Avicularin (Guavinosides C)		71
Guavinoside B		88
4,5-Diepipsidial A		88

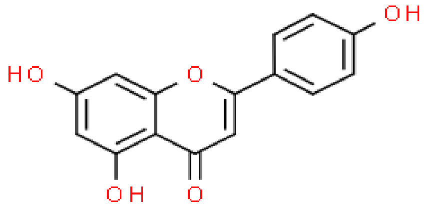
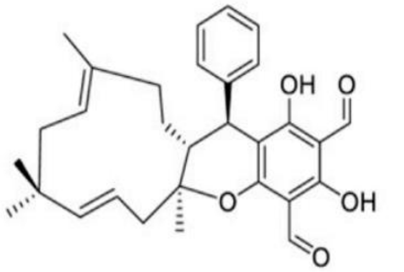
Apigenin		71
Guajadial B		88

Table 10: Structures of major phytochemicals present in *Carica papaya L.*

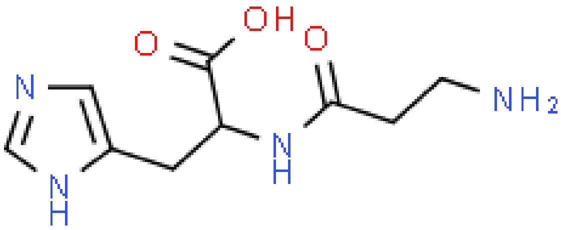
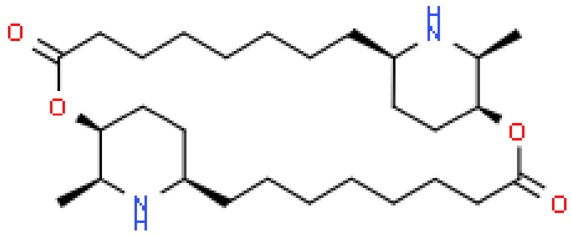
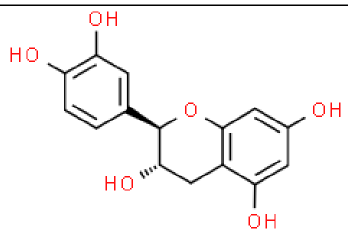
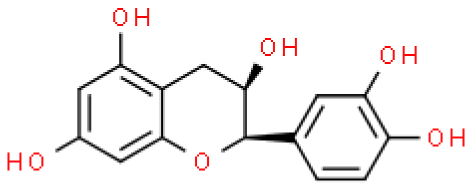
Compounds	Structure	Reference
Papain		71
Carpaine		71

Table 11: Structures of major phytochemicals present in coconut

Compounds	Structure	Reference
(+)-catechin		71
(-)-epicatechin		71

Results and Discussions

Fruits play an important part in Asian culture, cuisine, and traditional medicine. This has sparked significant interest in the potential benefits of these fruits for human health. To explore these benefits, various methods are being studied and researched. Asia, being one of the leading continents in the production of diverse fruit varieties, has gained particular attention. This review focuses on the ten most common fruits

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found across Asia. These fruits either originate from Asia or have spread throughout the region by birds, humans, and other means. While the history of their origins is still debated, these fruits are widely grown for their taste, nutritional value, and health benefits, and, in some cases, for survival purposes.

Fermentation is an age-old process used to extend the shelf life of food and offer other benefits. Not only does fermentation increases shelf life, but it also enhances the nutritional value and taste of the product. Fermentation can occur naturally or be induced by adding bacterial cultures. In the review, the most efficient and feasible methods are preferred. For instance, noni, dragon fruit, rambutan, and durian undergo natural fermentation without the addition of microorganisms. in contrast, mango, mangosteen, jackfruit, guava, papaya, and coconut are fermented through the inoculation of organisms. The choice between natural and inoculated fermentation depends on various factors. Inoculating organisms and inducing fermentation is the most common practice today because it significantly reduces the risk of contamination and increases the likelihood of obtaining a successful fermented product. Naturally fermented samples are more susceptible to variations due to environmental factors such as temperature, contamination risks, and the fermentation environment. The organisms selected for fermenting fruits are based on their availability, feasibility, and growth nature. Previous studies provide insights into the appropriate organisms for each fruit.

Microbes play a crucial role in fermentation. One of the most known organisms involved in this process is lactic acid bacteria. In this review, the presence of microorganisms is studied based on the isolation of organisms from each fermented fruit sample. Naturally fermented fruit samples revealed the presence of organisms that might be responsible for fermentation or the growth of different species that may or may not contribute to the fermentation process. Fruits that were fermented by inoculating with specific organisms showed the growth of those species. *Lactobacillus plantarum* was one of the common species, found in six out of ten fruits studied. Specifically, *Lactobacillus plantarum* was present in mangosteen, durian, guava, papaya, coconut and mango. The second most common species was *L. casei,* which was present in mango, mangosteen, and jackfruit. The review also includes other isolated organisms from the fermented fruit samples. These organisms are significant in determining the quality of the fermented products and contribute to various factors such as taste, odour, and colour.

In addition, the fermentation process can produce bioactive substances such as polyphenols, antioxidants, and vitamins, all of which add to the health advantages of fermented fruit products. These bioactive chemicals have been associated with a range of health-promoting properties, including anti-inflammatory, anti-cancer, and cardiovascular benefits. All ten fruits selected for this review share antioxidant and anti-inflammatory effects. In addition, noni, pitaya, mango, guava, papaya, and coconut possess antidiabetic properties, whereas rambutan, mangosteen, and jackfruit exhibit antibacterial properties. Durian is noted for its anticancer properties. Further, each fruit displays various properties depending on its phytochemical content and contribution to health. Among the phytochemicals present, quercetin and rutin are particularly prominent. However, the health benefits of fermented fruit products may vary based on the specific fruits used, fermentation conditions, and individual dietary patterns. Although fermented fruits can provide several health benefits, they should be taken in moderation as part of a balanced diet, especially for individuals with diabetes or alcohol-related disorders. Overall, fruit fermentation in Asia not only shows diversity but also offers a range of potential health advantages, showing its significance towards consumption.

Comparison of Fermentation Methods

Each of the ten fruits' fermentation processes offers a unique perspective on fermentation, showcasing a combination of conventional and modern techniques. Conventional techniques, such as those used for rambutan, durian, and noni, depend on environmental factors, natural microbial flora, and minimal intervention. For example, rambutan utilizes banana leaves to produce an anaerobic environment. According to a study by Chai,[90] the rambutan fruits were completely covered with banana leaves that had been rinsed with tap water to establish an approximately anaerobic condition. The setup was then moved to an incubator cupboard (30±2 °C) for fermentation. In contrast, noni juice ferments using its intrinsic enzymes[91], a few days after harvest, ripe noni fruit is extremely prone to softening and deterioration, a condition linked to intrinsic enzymes found in microorganisms such as *Gluconobacter fracteurii* and *Microcor circinelloides.* Differing from others, durian paste (tempoyak) uses salt to stimulate lactic acid fermentation.[92] These techniques are relatively accessible while ensuring the effective utilization of resources.

Modern methods involve pasteurization and the use of specific LAB strains, such as *Levilactobacillus brevis*, *Lacticaseibacillus casei*, and *Lactobacillus plantarum,* to control and enhance the fermentation process. This approach has been demonstrated with mango, mangosteen, and papaya. Mangosteen and papaya juices are adjusted with additional substrates; for instance, a study by Soaib[93] used unrefined sugar because it contains naturally occurring minerals and nutrients that promote microbial activity and growth, making the fermentation process more effective. The fruits were incubated under specific conditions, whereas mango juice was pasteurized and inoculated with LAB strains.[94] These techniques ensure enhanced probiotic activities and consistent product quality. Aseptic preparation and regulated fermentation environments are simplified by the fermentation of dragon fruit and coconut water. Coconut water is injected with LAB strains and preserved at optimal temperatures, while dragon fruit ferments naturally without external inoculation. By combining yeast and acetic acid bacteria, the jackfruit technique reveals the variety of microbes that may be used in fermentation.[95]

The fermentation methods for the ten selected fruits−noni, dragon fruit, rambutan, mango, mangosteen, durian, jackfruit, guava, papaya, and coconut, show different fermentation processes that use different microbiological applications. Every fruit uses techniques designed to maximize its health and nutritional value based on its unique qualities. Specific fermentation procedures are tailored to each fruit, and LAB is essential in these thoroughly controlled processes by converting sugars into lactic acid. This transformation not only preserves the fruit but also increases its probiotic value.

Microbial Diversity and Functions

Fruit fermentation greatly improves the nutritional and sensory qualities of products due to the variety of microbes involved.[96] A study by Doo[97] has highlighted the diversity of Lactic Acid Bacteria (LAB), found in Asian fermented foods, emphasizing the use of LAB-rich fermented foods as a safe, all-natural way to improve health and prevent diseases. Notable benefits of LAB in fermentation products are evident in studies by Mathur, Mora, and Bintsis.[98,99,100] Consuming LAB from fermented fruits offers three primary benefits: improving the health of the digestive tract and treating chronic gastrointestinal illnesses, regulating the immune system and providing anti-inflammatory effects to prevent immune-related diseases, and synthesizing vitamins and other bioactive compounds to enhance human health. Generally, LAB are gram-positive bacteria that primarily rely on carbohydrates for carbon and are well-known for their exceptional resistance to low pH.[101] These bacteria are typically found in fermented fruits due to their metabolic characteristics, which include acid production, odor generation, protein hydrolysis, and the efficient suppression of spoilage bacteria.[102]

Specifically, *Lactobacillus plantarum* is one of the common bacteria present in the reviewed fruits. The gram-positive, rod-shaped bacterium *Lactobacillus plantarum* can survive in the human gastrointestinal tract and is widely used as a probiotic.[103] It can be isolated and grown at temperatures between 16 and 30˚C and at pH levels near 4. However, such explanations tend to overlook the fact that probiotic strains of *Lactobacillus plantarum* exhibit reasonable resistance to low pH levels, as low as 3.2, and low temperatures (4–8 °C) in fruit juice. For example, in a study by Plessas,[104] the viability of probiotic *L. plantarum* NCIMB 8826 declined when cranberry, pomegranate, and lemon juices with initial pH values of about 3 were stored at 4°C. Cells remained viable until the 35th day only in the case of lemon and lime juice. Depending on the carbon supply, *Lactobacillus plantarum* can switch between heterofermentative and homofermentative metabolism, producing lactic acid, ethanol, acetic acid, and carbon dioxide. Besides the ten fruits

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reviewed, a study by Yang[105] involved two commercial *Lactobacillus plantarum* strains to ferment a beverage containing apples, pears, and carrots. The study revealed that the fermented beverage made from those fruits had noteworthy antioxidant activity which provides a health benefit to humans.

Besides the most common *Lactobacillus plantarum,* which has been isolated from ten selected fruits, other LAB species have also been identified, including *Enterobacteriaceae, Acetobacteraceae, Enterococcus faecalis*, *E. durans*, *Levilactobacillus brevis*, *Lacticaseibacillus casei, Lactiplantibacillus plantarum subsp. plantarum, Lacticaseibacillus rhamnosus, Pediococcus pentosaceus, L. fermentum*, *Fructobacillus durionis*, *L. acidophilus*, and *Lactobacillus helveticus*. The beneficial health effects of fermented fruits can be increased by a range of bioactive compounds that different strains of bacteria produce, including exopolysaccharides, vitamins, and bacteriocins.[106] The interaction of LAB and other microorganisms produces distinct aromas and flavours, improving the sensory qualities of the final product through the fermentation process.[107] A well-known example of this is the unique qualities of traditional fermented fruit products, such as noni juice and tempoyak (fermented durian paste), which are largely attributed to this microbial synergy.[108] The metabolic activities of these bacteria are primarily responsible for the health benefits associated with fermented fruits, which have become an integral part of both traditional and modern Asian diets.

Challenges and Limitations

The standardization of the fermentation process remains a significant challenge, as different raw materials and fermentation conditions can result in products with varying qualities.[109] Variations in fruit ripeness, sugar concentration, and microbial populations can impact the fermentation process, leading to a range of flavours, textures, and nutritional contents.[110] To address these challenges standardized processes for fruit preparation, fermentation, and storage must be established. This will ensure consistency in the final products, increasing their reliability for consumers and researchers.

Regarding the challenges and limitations of fruit fermentation, safety is another major concern. The safety of the final product itself may be compromised if harmful microbes contaminate it during the fermentation process.[111] In addition, improper regulation of the fermentation process can lead to the production of contaminants such as mycotoxins and biogenic amines. While biogenic amines play a role in cell growth control, differentiation, and gene regulation, they can have adverse effects if their levels exceed safe thresholds.[112] To reduce these risks, strict quality control procedures must be established, including routine microbiological testing and parameter monitoring during fermentation.

Regarding the unrefined sugar used during fermentation, it can have both benefits and drawbacks as a substrate. Generally, unrefined sugar can enhance the flavour and nutritional content of the fermented product by providing additional nutrients that encourage microbial development.[113] The quality of the final product and the fermentation process, however, may be impacted by compositional variations and the possible presence of contaminants. To use unrefined sugar effectively in fermentation, it is crucial to ensure its quality is consistent and to understand how it affects microbial activity.

Understanding these challenges can help improve future product development. While fermenting fruits can enhance their sensory qualities and offer many health benefits, several issues must be resolved to ensure scalability, uniformity, and safety. To overcome these challenges and fully realize the potential of fermented fruits, it is essential to standardize fermentation processes, implement strict quality control measures, and use cutting-edge technology for industrial applications. Addressing these issues can maximize the production and consumption of fermented fruits, providing a reliable source of nutrients and health benefits to a larger population.

Future Directions and Research Needs of Fruits Fermentation

To improve the health benefits and sensory qualities of fermented fruits, future research should focus on developing novel fermentation processes and investigating new microbial strains. Genetic engineering could play a role in creating microbial strains with improved probiotic properties or the ability to create novel bioactive compounds. Additionally, studies should investigate the synergistic effects of combining several microbial strains to produce starter cultures with a broader range of health benefits.

The positive health benefits demonstrated in laboratory and animal studies must be confirmed through clinical trials involving humans, especially for conditions like metabolic disorders, cardiovascular diseases, and gastrointestinal problems. Promoting the regular consumption of fermented fruits can be achieved by incorporating them into appealing and convenient products like drinks and snacks. Awareness campaigns and improved accessibility through local markets and online platforms are crucial for achieving broad acceptance and consumption. High-quality fermented fruit products with significant health benefits can be realized by addressing challenges related to standardization, safety, and consistency through advanced technologies such as automated fermentation systems and real-time monitoring.

Conclusion

Fruits are essential for enhancing human health and are a gift from nature. They offer a wealth of nutrients, antioxidants, and fibre, provide defence against many ailments, and enhance overall well-being. Fruits not only boost our health and allow us to indulge in the mouth-watering flavours that nature has to offer. Although the origin of various fruits is diverse, many are now grown in Asia and are economically beneficial to the continent. Fermentation of fruit enhances their flavour, texture, and taste, making them more appealing for consumption. It also prolongs shelf life, making storage easier for consumers. Lactic acid bacteria play a major role in fermentation, directly influencing improvements in health. The different components present in the fruit help to improve human health naturally. In conclusion, the ten fruits discussed in this review–noni, dragon fruit, rambutan, mango, mangosteen, durian, jackfruit, guava, papaya, and coconut–each have unique fermentation processes, microbial profiles, and health benefits. This review aims to highlight the importance of fermented fruits and their health advantages. Further studies could explore additional fruits of interest, such as pomelo, longan, lychee, watermelon, kiwi, soursop, sweet cherry, goji berry, star fruit, passion fruit, orange, and apple, which are also found in and around Asia.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Declaration

The authors hereby declare that the work presented in this article are original and that any liability for claims relating to the content of this article will be borne by them.

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