

Nutritional Composition and Therapeutic Potential of Pineapple Peel- A Comprehensive Review

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Pineapple (*Ananas comosus*), the succulent and vibrant tropical fruit, is a symbol of exoticism and sweetness that captures the hearts and palates of people around the world. The pineapple peel, often considered as waste, has garnered attention for its potential applications. The pineapple peel is rich in essential nutrients, including calcium, potassium, vitamin C, carbohydrates, dietary fiber, and water, making it beneficial for the digestive system, weight management, and overall balanced nutrition. It contains significant amounts of sugars such as sucrose, glucose, and fructose, along with citric acid as the predominant organic acid. The peel also contains bromelain, a proteolytic enzyme known for its digestive properties. Studies

have highlighted the pharmacological properties of pineapple peel, such as its potential anti-parasitic effects, alleviation of constipation, and benefits for individuals with irritable bowel syndrome (IBS). Efforts are being made to promote the utilization of pineapple peel as a valuable resource rather than mere waste. Its applications range from the production of vinegar, alcohol, and citric acid to the development of various food products, including squash, syrup, jelly, and pickles. Further research and innovation are required to fully explore the potential of pineapple peel and establish sustainable practices for its utilization, contributing to waste reduction and the development of value-added products.

Introduction

Pineapple, which is also known as *Ananas comosus*, belongs to the family *Bromeliaceae* is one of the most significant commercial fruit crops in the world. Due to its exquisite flavour and taste, it is referred to as the “queen of fruits”. Pineapple holds the rank of being the third most crucial tropical fruit worldwide, following the popularity of banana and citrus fruits. Worldwide, this fruit juice is ranked third after orange and apple juices.^[1] One of India’s most significant commercially grown fruit crops is the pineapple. The projected yearly global fruit production is 14.6 million tonnes. With 1.2 million tonnes produced annually, India ranks seventh among pineapple producers. Thailand, the Philippines, Brazil, China, Nigeria, Mexico, Indonesia, Colombia, and the United States are additional top producers. Brazil is where pineapple cultivation first began, and it then extended to other tropical regions of the

world. Costa Rica was the top producer of pineapples in 2019, growing more than 3 million tons of fresh fruit, according to the UN Food and Agriculture Organisation’s (FAO) crop database. Since 1995, the size of pineapple plantations has expanded more than seven times, which has had a major adverse impact on the ecosystem (2). Over 100 different pineapple cultivars exist globally at the moment. Based on their economic properties, they may be categorised into five groups: Cayenne, Queen, Spanish, Abacaxi, and Maipure. Each variety has a distinct set of sensory qualities of its own. Abacaxi, Queen, Red Spanish, Kona Sugarloaf, Pernambuco, Panare and Singapore Red are some more pineapple cultivars that are farmed for commercial purposes. The Red Spanish, Perola and Manzana kinds are often farmed locally in their original markets, while the Cayenne, Singapore Spanish and Queen cultivars are the most commercially valued traditional pineapple cultivars globally. Because of its excellent fresh fruit processing qualities and great output potential, the Smooth Cayenne cultivar rose to prominence and has dominated the market since the 1800’s (3). Assam, Meghalaya, Tripura, Manipur, West Bengal, Kerala, Karnataka, and Goa are among the states where pineapple is cultivated. Gujarat, Maharashtra, Tamil Nadu, Andhra Pradesh, Orissa, Bihar, and Uttar Pradesh are the other states where it is cultivated on a small basis. The plant has a height range of 75–150 cm and a spread range of 90–120 cm. It is small, has a thick stump, and has slender, fibrous leaves. The plant matures into a fruit with a crown at the top that is cone-shaped, juicy, and meaty.^[4]

Fresh, cooked, juiced, and preserved pineapples are all consumed or served around the world. This fruit is seasonal and due to its high moisture content extremely perishable. A considerable amount of bromalin, a protein-digesting enzyme, citric acid, malic acid, and vitamins A and B are also present in

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mature fruit, which also includes 14% of sugar.^[1] The fruit is an excellent source of calcium, magnesium, potassium, iron, and vitamins A, B, and C. Additionally, it is an excellent source of the digestive enzyme bromelain. The composition of pineapple juice varies based on the region where it's cultivated, time of year, harvesting method, and process. The flavour of pineapple fruit is refreshing because of the fruit's sugar and acid balance. One of India's most significant commercially grown fruit crops is pineapple of which projected yearly global fruit production is 14.6 million tonnes. Pineapple fruits have high levels of moisture, sugars, ascorbic acid, soluble solids, and low levels of crude fibre. As a result, pineapple can be utilised as a fruit supplement for good health.^[5] Typically, fresh pineapple fruit or fresh pineapple juice are consumed all over the world. It is only essential to remove the crown, rind, eyes, and core from field-ripe fruits in order to consume them fresh. Fresh, canned, and juiced pineapple can be found in a variety of foods, including desserts, fruit salads, jam, yogurt, ice cream, confectionery and dishes with meat. Green pineapple may also be used for the preparation of pickles. In India, canned slices and juice account for around 70% of production because to their high demand (1). A variety of foods are made from pineapple, including squash, syrup, and jelly. Pineapple is also utilized in the production of vinegar, alcohol, citric acid, calcium citrate, and various other commodities. Small sized pineapples are harvested from the plant in Panama, leaving a few inches of stem attached for use as a handle. The flesh of bigger fruits is divided into different portions and consumed in a variety of ways, including fresh, as a dessert, in salads, compotes, and other dishes, as well as cooked in pies, cakes, and puddings, or used as a garnish on ham, or prepared into sauces or preserves. The fermented pulp is used to create a popular sweetmeat in the Philippines. The pineapple tends to acquire off tastes when frozen, thus freezing it is not recommended. Africans consume young, tender shoots in salads. Bromelain is a digestive enzyme classified as a proteolytic by the United States National Library of Medicine. When consumed with meals, bromelain promotes the breakdown of proteins into amino acids, assisting in the digestion of proteins thus pineapple is also advised as a therapeutic diet for people suffering from various diseases.^[1]

Fresh pineapple exports from India have seen a significant growth, going from 138 tonnes in 1999–2000 to 837 tonnes in 2001–2002. Some significant nations that import pineapple from India are the United Arab Emirates, Saudi Arabia, Oman, and Nepal. Though pineapple exports have been on the rise, there is a lack of consistency in our exports, which is not a desired trait given that a constant supply to a market is one of the key requirements for successful exports. In 2001–2002, over 70% of the production was exported. Pineapple can grow well in the humid tropics. As long as the temperatures are not too high, the fruit may grow both in the interior and close to the sea coast. 22–32 °C is the ideal temperature for growing to be effective. A difference of at least 40 °C between daytime and night-time temperatures is ideal since high temperatures at night are harmful to plant growth (5).

Nutritional Composition of Pineapple and its Peel

The pineapple is a great tropical fruit that offers a lot of health advantages along with outstanding juiciness and vibrant tropical flavour.^[6] The significant amounts of calcium (10.88 mg/100 g), magnesium (12.68 mg/100 g), potassium (143 mg/100 g), phosphorus (13.56 mg/100 g), vitamin C (36.37 mg/100 g), carbohydrates (9.42 g/100 g), dietary fibre (3.46 g/100 g), water, and other minerals, low salt and fat (0.16 g/100 g) found in pineapple are helpful for the digestive system, aid in maintaining a healthy weight, and promote balanced nutrition.^[7] Pineapple has a moisture content of 81.2 to 86.2% and a total solids content of 13 to 19%, the primary sugars being sucrose, glucose, and fructose. Up to 85% of all solids are made up of carbohydrates, whereas just 2% to 3% are made up of fibre. Citric acid is the most prevalent organic acid in pineapple.^[1] A very small amount ash, nitrogenous chemicals, and lipids (0.1%) are present in the pulp. True proteins make up 25–30% of nitrogenous substances. Out of this percentage, a protease known as Bromelain is responsible for 80% of the proteolytic activity.^[7] Ascorbic acid, which is commonly found in pineapple juice, is a rich source of vitamin C. A powerful antioxidant, ascorbic acid, or vitamin C, aids in the body's absorption of iron and fights viral and bacterial infections. Half of the daily recommended amount of vitamin C for adults is present in one cup of pineapple juice.^[1] Pineapples contain a number of important minerals, including manganese, a trace mineral important for the development of bone as well as the production and activation of certain enzymes. Copper is another trace mineral that is present in pineapples. It controls blood pressure and heart rate and aids in iron absorption.^[8]

In India, Kew and Queen pineapple variants are the most significant and promising commercial variety. These are the most widely cultivated varieties. Mauritius, Charlotte, Rothchild, Jaldhup, Desi, and Lakhat are some other varieties that are cultivated. The shape of Kew is oblong, large (1.5–2.5 kilogramme), and tapered towards the crown. When mature, the flesh is a pale golden colour and highly juicy. In comparison to Kew, Queen is smaller (0.9–1.3 kg), with flesh that is rich golden yellow, less moist, crisp-textured, and flavoured with a pleasant scent. According to Hossain *et al.*, the Honey Queen variety of pineapple is sweeter and possesses a higher nutrient content in comparison to the Giant Kew variant. The Giant Kew variety has 1.75% of the non-reducing sugar, 3.88% of the total sugar, and 6% of total soluble solids (TSS). The Honey Queen type, on the other hand, has 10% of the TSS, 4.84% of the total sugar, and 1.59% of the non-reducing sugar. Giant Kew contains more Vitamin C than Honey Queen, but Honey Queen has a higher concentration of all the minerals. Comparing the two varieties, the Honey Queen has more calcium than the Giant Kew.^[9] In Nigeria, pineapple has an ascorbic acid value between 22.5 and 33.5 mg/100 g-fw. When compared to pineapple waste, pineapple pulp had more reducing sugar (10.5%). The Indian variety of pineapple waste exhibited a higher total sugar content (9.75%) compared to its pulp (8.66%). On the other hand,

Brazil's pearl pineapple contained 14.5% of the total sugar content. Depending on the season and maturation level, TSS ranges from 10% to 14% brix. It is observed that Indian varieties of pineapple have less reducing sugar (10–12.5). However, the reducing sugar content of Ghanaian pineapples is more significant (16.5%). In Indian pineapple, pulp had a higher TSS value (13.3%) than pineapple waste (10.2%). The Malaysian Josapine pineapple's TSS Value was 13.5%. The ascorbic acid level of pineapple fruits marginally reduced as they ripened. The pineapple waste demonstrated a high moisture content of 91.35% and a moderate level of titratable acidity. Pineapple's moisture content ranges from 69 to 89.5%. However, it reduced over the time of ripening and storage at room temperature.^[11]

Pineapple peel is a by-product of pineapple processing and is often discarded as waste. However, recent studies have shown that pineapple peel contains various nutrients and bioactive compounds that have potential health benefits. Pineapple peel is a good source of dietary fibre, vitamins, and minerals. The peel of pineapple contains various phenolic compounds, including flavonoids, phenolic acids, and tannins as mentioned in Table 1. It was found that pineapple peel extract contains several phenolic compounds, such as ferulic acid, caffeic acid, and quercetin. Pineapple peel contains about 12–14% dietary fibre, including both soluble (5.90 ± 0.19 g/100 g) and insoluble fibers (36.3 ± 0.79 g/100 g). It also contains significant amounts of vitamin C, vitamin A, potassium, and calcium^[1,10–12] as summarized in Table 2. These compounds have been shown to have antioxidant, anti-inflammatory, and anticancer properties. Pineapple peel also contains bromelain, a group of proteolytic enzymes that have been shown to have anti-inflammatory and anticancer effects. According to a study, pineapple peel extract contains about 0.23% bromelain activity.^[13] The peels contain various carotenoids, including beta-carotene, lycopene, and xanthophylls. These compounds have been shown to have antioxidant properties and may help protect against chronic diseases such as cancer and cardiovascular disease.^[11] Pineapple peel also contains essential oils, which have been shown to have antibacterial and antifungal properties. A study found that pineapple peel oil has significant inhibitory effects against various pathogenic bacteria and fungi.^[1] Fibers play important roles in the body such as interfere in the metabolism of lipids and carbohydrates, act against constipation, and promote feelings of satiety, thus being considered as a functional food.^[5]

Pineapple peel has been traditionally used in many cultures for various therapeutic purposes. Pineapple peel contains bromelain that have been shown to have anti-inflammatory effects and wound healing properties. It was found that bromelain extracted from pineapple peel has significant anti-inflammatory activity and may be useful in the treatment of inflammatory conditions such as arthritis along with can accelerate the healing of diabetic foot ulcers.^[15] Due to the presence of various bioactive compounds whose chemical structures are given in Table 3, including phenolic compounds, carotenoids, and bromelain, pineapple peel extract has shown significant anti-cancer activity against several cancer cell lines, including breast, colon, and lung cancer cells and can help

Table 1. Comparison of phytochemicals present in pineapple peel and fruit.

Phytochemicals	Peel	Fruit
α -amylase	–	–
Acid phosphatase	–	–
Alkaline phosphatase	–	–
Alkaloid	+	+
Amino acids	+	+
Anthraquinones	+	–
Bromelain	+	+
Carbohydrate	+	–
Cardiac Glycoside	–	+
Coumarins	+	–
Flavonoids	+	+
Glycoside	+	–
Inulin	+	+
Naphthoquinones	–	+
Oxalate	+	–
Peroxidase	–	–
Phenols	+	+
Phytate	+	–
Phytosterols	–	+
Polyphenols	+	+
Protein	+	+
Quinine	+	–
Ribulose biphosphate carboxylase	–	–
Saponin	+	+
Steroids	+	+
Sterols	+	–
Tacorin	–	–
Tannins	+	+
Terpenoids	+	+
Triterpenes	+	–

reduce blood pressure and improve lipid profile in rats with high blood pressure, thus possessing anti-cancer properties and cardiovascular benefits.^[13]

Pineapple peel contains dietary fiber, including both soluble and insoluble fibers that has significant prebiotic activity and can promote the growth of beneficial gut bacteria in turn promoting digestive health.^[17] Overall, these studies suggest that pineapple peel has various therapeutic properties, including anti-inflammatory, anti-cancer, digestive, cardiovascular, and wound healing properties.

Pharmacological Properties and Health Benefits of Pineapple Peel

In the twenty-first century, when the amount of waste produced is a nuisance to man and his environment, the waste

Table 2. Nutritional composition of pineapple peel.

Nutrient	Amount (g/100 g peel)	Reference
Crude protein	9.13 ± 0.25	[10]
Crude lipid	5.31 ± 0.74	[12]
Total dietary fiber	42.2 ± 0.89	[10]
Insoluble dietary fiber	36.3 ± 0.79	[10]
Soluble dietary fiber	5.90 ± 0.19	[10]
Ash	4.81 ± 0.03	[10]
Carbohydrate	42.3	[10]
Moisture	82.7 ± 1.91	[10]
Xylose	7.83 – 9.23	[12]
Uronic acid	6.83 – 8.26	[12]
Cellulosic glucose	8.33 – 10.7	[12]
Potassium	938.48 mg/kg	[42]
Phosphorus	1.12 g.kg ⁻¹	[10]
Calcium	2.80 g.kg ⁻¹	[10]
Magnesium	0.56 g.kg ⁻¹	[10]
Copper	1.46 g.kg ⁻¹	[10]
Iron	28.40 g.kg ⁻¹	[12]
Manganese	24.56 g.kg ⁻¹	[12]
Zinc	8.97 g.kg ⁻¹	[12]
Vitamin C	26.5 mg/100 g	[1]
Threonine	1.50 ± 0.01 g.kg ⁻¹	[12]
Valine	2.00 ± 0.01 g.kg ⁻¹	[12]
Methionine	0.40 ± 0.01 g.kg ⁻¹	[16]
Isoleucine	1.00 ± 0.01 g.kg ⁻¹	[16]
Leucine	1.20 ± 0.01 g.kg ⁻¹	[16]
Phenylalanine	0.80 ± 0.01 g.kg ⁻¹	[16]
Lysine	2.10 ± 0.01 g.kg ⁻¹	[16]
Tryptophan	0.90 ± 0.01 g.kg ⁻¹	[16]
Aspartic acid	11.30 ± 0.01 g.kg ⁻¹	[16]
Glutamic acid	6.30 ± 0.01 g.kg ⁻¹	[16]
Serine	3.20 ± 0.01 g.kg ⁻¹	[16]
Glycine	2.50 ± 0.01 g.kg ⁻¹	[16]
Histidine	0.60 ± 0.01 g.kg ⁻¹	[16]
Arginine	2.70 ± 0.01 g.kg ⁻¹	[16]
Alanine	2.10 ± 0.01 g.kg ⁻¹	[10]
Proline	0.70 ± 0.01	[10]
Tyrosine	0.80 ± 0.01	[10]
Cysteine	0.10 ± 0.01	[10]

to wealth programme should be a crucial component of sustainable living. In addition to helping with digestion, pineapple peels have also been associated with a decrease in intestinal parasites, constipation, and symptoms of irritable bowel syndrome (IBS). They also aid in keeping healthy gut flora. Recently, solid-state fermentation technology and a green chemistry approach were used to produce value-added products from pineapple peel.^[18] It operates as an anti-inflammatory in the sinuses and throughout the body and it is advised for reducing swelling after surgery or injury. The high vitamin C

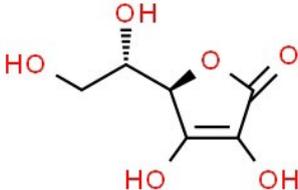
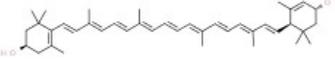
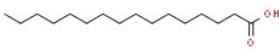
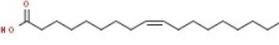
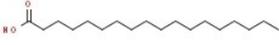
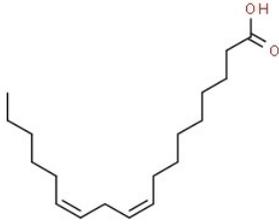
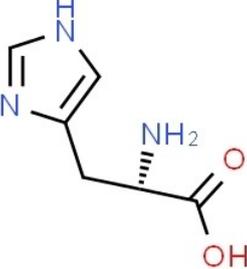
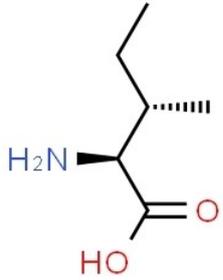
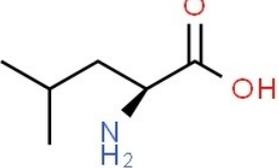
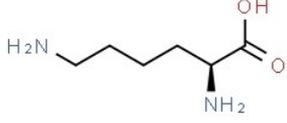
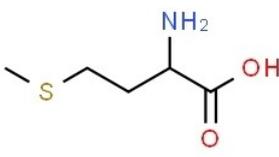
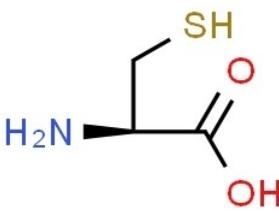
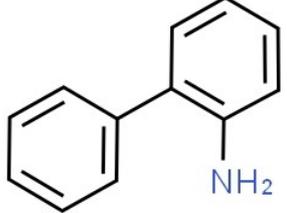
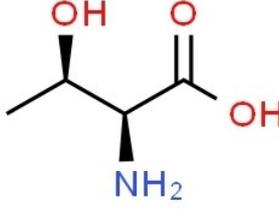
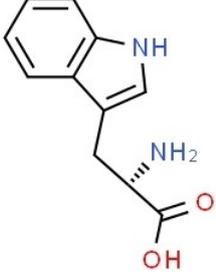
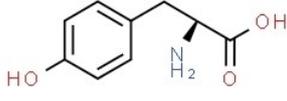
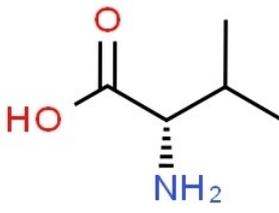
content of pineapples and their skin helps to prevent and treat infections as well as potential IBS symptoms. They aid in establishing a balanced gut flora. Antimicrobial, antimalarial, anti-inflammatory, antidiabetic, antioxidant, and anticancer actions are only a few of the documented medicinal properties of pineapple peels as shown in figure 1. This suggests that pineapple peel may be a potential source of significant bioactive substances with several medicinal applications.^[19]

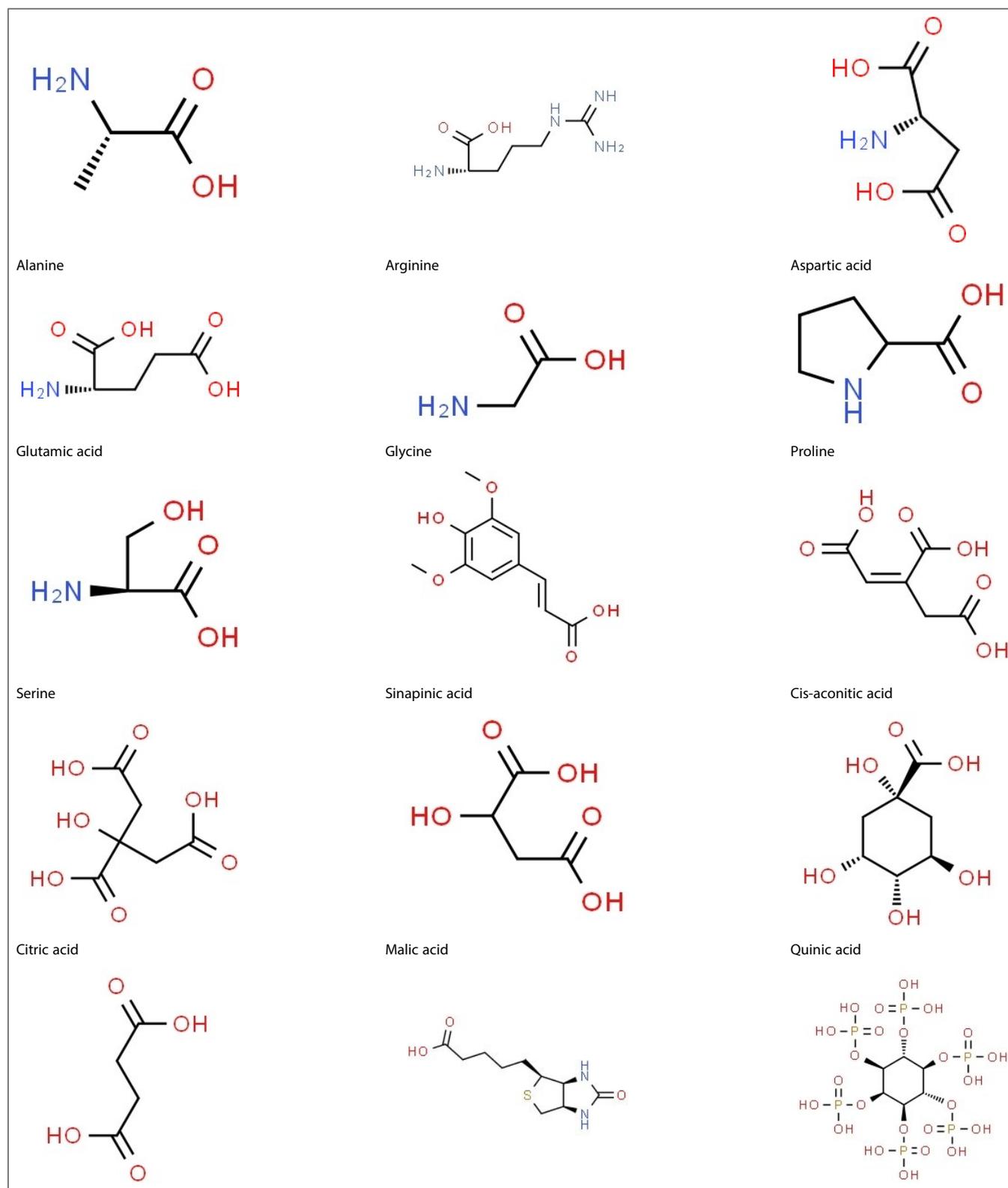
Bromelain, a powerful enzyme and cysteine protease which is abundant in pineapple. It helps to lessen inflammation in the body and is present in high amounts in the skin and stems of pineapples. Bromelain and vitamin C have antibacterial, mucus-cutting, cough-suppressing, wound-healing, and overall system boosting properties in the body.^[19] In persons with arthritis, bromelain also has anti-inflammatory properties. Making a cure using pineapple peels immediately addresses the source of the discomfort. Beta carotene and vitamin C, which assist to combat glaucoma and other degenerative eye diseases, are present throughout the entire plant. Manganese, which helps to reduce inflammation in the tissues and gums, is also abundant in pineapple skins. Manganese helps in bone and tooth formation, strengthening, and repair. Its astringent properties and vitamin C content keep gums clear and healthy, which is beneficial for dental health.^[19] Early studies have shown that antioxidants, vitamin C, bromelain, and manganese levels in the skin can help prevent cancer and fight tumours. Bromelain inhibits the formation of blood clots, and pineapple juice's high iron and copper content encourages the creation of healthy red blood cells. Potassium can counteract excessive salt intake and maintain healthy blood vessels, which keeps blood pressure stable. Women who are attempting to get pregnant typically need to watch what they eat. Reduced uterine inflammation contributes to the formation of the ideal environment for implantation.^[19]

Antioxidant Properties

Antioxidant properties refer to the ability of certain substances to neutralize or inhibit the damaging effects of molecules called free radicals in the body. Free radicals are highly reactive molecules that can cause oxidative stress and damage to cells, proteins, and DNA. This damage has been linked to various diseases, including cancer, cardiovascular disease, and neuro-degenerative disorders. Antioxidants work by donating an electron to stabilize free radicals, thereby preventing them from causing damage. They help to maintain the balance between the production of free radicals and the body's ability to counteract their harmful effects.^[20] There are several different types of antioxidants, including vitamins (such as vitamin C and vitamin E), minerals (such as selenium and zinc), and phytochemicals (found in plant-based foods), such as flavonoids and carotenoids.^[21] Pineapple peel contains a significant amount of ascorbic acid in it which is a powerful antioxidant. The production of collagen in bones, blood vessels, cartilage, and muscle, as well as the absorption of iron, are both supported by vitamin C. Additionally, vitamin C lowers the risk of developing

Table 3. Chemical structures of various constituents of pineapple peel.

 <p>Ascorbic acid</p>	 <p>Lutein</p>	 <p>Palmitic acid</p>
 <p>Oleic acid</p>	 <p>Stearic acid</p>	 <p>Linoleic acid</p>
 <p>Linolenic acid</p>	 <p>Histidine</p>	 <p>Isoleucine</p>
 <p>Leucine</p>	 <p>Lysine</p>	 <p>Methionine</p>
 <p>Cysteine</p>	 <p>Phenylalanine</p>	 <p>Threonine</p>
 <p>Tryptophan</p>	 <p>Tyrosine</p>	 <p>Valine</p>



some cancers, such as colon, oesophageal, and stomach cancers, and delays the onset of urinary tract infections during pregnancy.^[8] According to the John Hopkins COVID-19 dashboard, as of December 30, 2020, the severe coronavirus 2 acute

respiratory syndrome (SARS-CoV-2) infection that caused the global COVID-19 pandemic was affecting more than 84,400 million people and killing more than 1799 million people worldwide. Recent studies have demonstrated that SARS-CoV-2

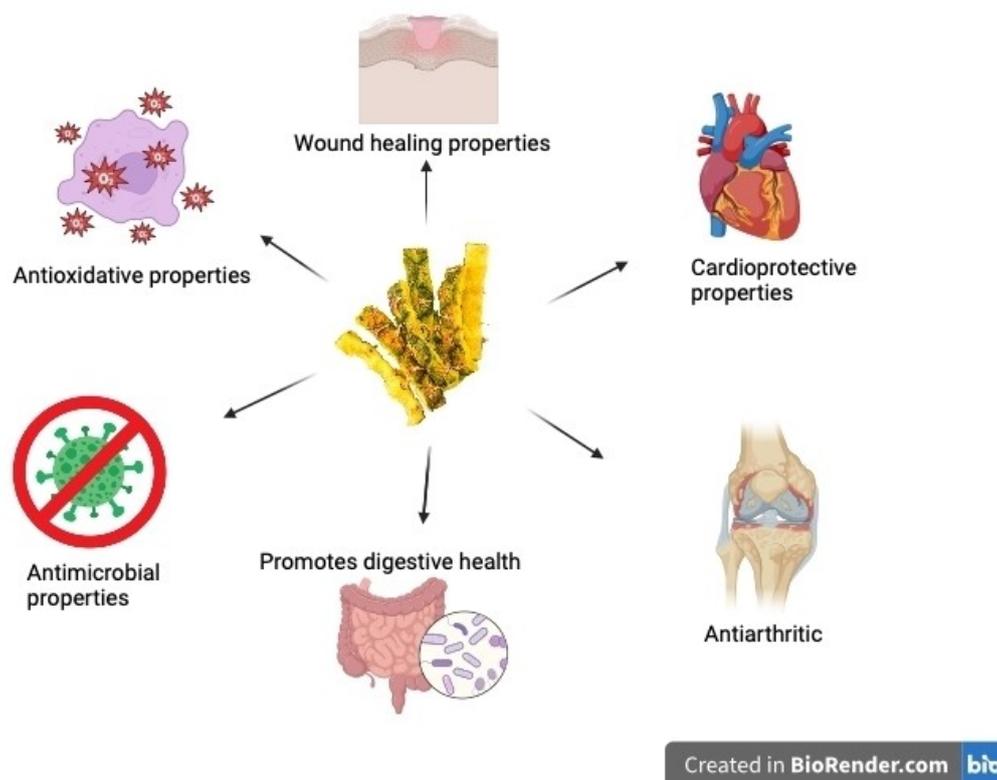


Figure 1. Pharmacological properties of pineapple peel.

binds to the angiotensin converting enzyme 2 (ACE2) binding site and stimulates the start of three different disease processes, including inflammation, coagulation, and cascade bradykinin.^[22] This activation causes a number of serious health issues, including acute respiratory syndrome, immune-suppression, and finally death. Some natural products have been demonstrated to lessen the negative effects of COVID-19 because to its possible antioxidant and anti-inflammatory characteristics. It has been demonstrated that the immunosuppressive properties of bromelain restrict the important pathogenesis related variables of COVID-19.^[23] These actions include the suppression of signalling pathways and, as a result, the depletion of inflammatory cytokines crucial for the development of SARS-CoV-2 syndrome and the generation of inflammatory cells. Additionally, bromelain lowers the enzyme needed to produce prostanoid, which lowers prostaglandins and thromboxane in turn lowering the pathways that lead to swelling and bleeding.^[24]

Anti-Inflammatory Properties

Bromelain, a proteolytic enzyme which is present in the pineapple peel is believed to show anti-inflammatory properties. It has demonstrated the ability to decrease the severity of inflammation in the colon.^[25] Its anti-inflammatory properties are attributed to its proteolytic action, which eliminates cell surface receptors associated with leukocyte defects and

activation.^[26] Additionally, bromelain affects the release of certain chemokines, leading to a decrease in the occurrence and frequency of persistent colitis. Consequently, bromelain is regarded as an innovative treatment for intestinal inflammation.^[27] When administered, bromelain reduces the levels of pro-inflammatory molecules such as interferon-gamma (INF- γ) and colony-stimulating factor in patients with inflammatory bowel diseases. Notably, patients with ulcerative colitis have experienced significant symptomatic improvement with the use of bromelain. Furthermore, bromelain has been shown to impede the release of specific chemokines, thereby mitigating the incidence and severity of colitis. Moreover, Bromelain has been found to have therapeutic benefits in treating sinusitis and can be utilized for managing the infection.^[24] Moreover, its affordability makes it an appealing alternative to conventional medical treatments. In the case of children with severe sinus infections, bromelain treatment has been observed to reduce the duration of symptoms and promote complete recovery in comparison to standard treatment approaches.^[28] Patients suffering from sinusitis have reported experiencing complete relief from breathing difficulties and nasal mucosal infection after using bromelain.^[29]

Cardioprotective Properties

Heart disease is the leading cause of global mortality, as reported by the World Health Organization (WHO). It claims

more lives each year than almost any other disease. In 2016, statistics revealed that cardiovascular diseases accounted for 31 % of all deaths worldwide, with a staggering 17.9 million individuals succumbing to these conditions. The majority of these deaths, approximately 85 %, were attributed to heart attacks or strokes. Alarmingly, individuals affected by these cardiovascular events were typically between the ages of 30 and 70 years old. Bromelain has demonstrated the ability to inhibit angina attacks, leading to symptomatic relief in hypertension.^[30] In vivo studies have shown that bromelain enhances cardiac efficiency, improves arterial flow, reduces arterial dissections, and promotes angiogenesis.^[15] Previous research indicates that bromelain treatment decreases apoptosis and endothelial cell damage in hepatic ischemia, and it has shown protective effects against muscle tissue hepatic encephalopathy injury.^[31] Bromelain also improves the permeability of blood vessel walls, leading to enhanced uptake of oxygen, nutrients, and improved blood fluidity.^[32] In experimental animal studies, long-term administration of bromelain has exhibited an antihypertensive effect, indicating that bromelain supplements may reduce risk factors associated with cardiovascular diseases.^[33] It is important to note that one of the main reasons for bromelain's anticancer property is its ability to inhibit blood platelet aggregation, which plays a crucial role in blood clotting.^[34] Bromelain has been found to exhibit fibrinolytic activity, inhibit thrombus formation, and reduce platelet aggregation, thus impeding blood clotting.^[33] This property of bromelain leads to thrombus destruction, reduced red blood cell clumping, decreased blood viscosity, and subsequently lowers the incidence of angina pectoris and transient cardiomyopathy attacks.^[35] Thrombophlebitis, an inflammatory process that contributes to the formation of blood clots and blockage of veins, particularly in the legs, can be alleviated by bromelain. Bromelain aims to minimize the potential complications of thrombophlebitis and aid in its recovery. Studies have indicated that bromelain effectively treats acute thrombophlebitis by reducing walking difficulties in patients and alleviating associated inflammatory symptoms such as skin temperature, tenderness, inflammation, and pain.^[33]

Antimicrobial Properties

Bromelain exhibits preventive effects against the growth of intestinal bacteria, including *Escherichia coli* and *Vibrio cholera*, and can also inhibit enterotoxigenic *Escherichia coli* (ETEC) bacteria. Studies have shown that bromelain can temporarily deactivate ETEC receptors in vivo by interacting with intestinal secretory signalling pathways, thus exerting its effects. It has demonstrated significant efficacy in defending against diarrhoea caused by *Escherichia coli* and can serve as a prophylactic measure against ETEC infection.^[36] Bromelain has also been documented to possess anti-helminthic activity against gastrointestinal nematodes such as *Trichuris muris* and *Trichostrongylus axei*.^[37] This implies that it can counteract various effects associated with intestinal pathogens. Furthermore, bromelain

has a synergistic effect when administered alongside antibiotics, and the exploration of these dual mechanisms can help uncover the benefits of bromelain against specific infections. Additionally, bromelain has been reported to act as an anti-fungal agent by inducing phagocytosis and pulmonary rupture killing of *Candida albicans*. It has also shown efficacy in treating Pityriasis lichenoides chronica, a skin condition caused by *Pityriasis lichenoides*, leading to complete cure.^[38] Studies have indicated that bromelain exhibits synergistic effects with certain antibiotics, such as amoxicillin, resulting in increased levels of these antibiotics in blood and urine during coadministration with bromelain.^[39] When combined with antibiotic treatment, bromelain has been found to be more effective than antibiotics alone in various respiratory infections, including influenza virus, chronic bronchitis, staph infection, thrombophlebitis, cellulitis, pyelonephritis, perirectal and rectal ulcers, sinus infections, and bladder infections.^[24] A formulation of bromelain, trypsin enzyme, and flavonoid pigment has been prescribed as an immunological agent combined with antibiotics for infants with septic shock. Additionally, bromelain has been found to increase protein consumption in elderly patients with reduced protein absorption when used in conjunction with enzymes derived from the *Aspergillus Niger* fungus.^[40]

Arthritis

Due to its affordability and widespread availability, bromelain is considered an excellent treatment option for arthritis, including rheumatoid arthritis. It serves as a potent pain reliever and exerts a notable impact on pain mediators like bradykinin, which is involved in smooth muscle contraction and blood vessel dilation. Bromelain has demonstrated significant effectiveness in reducing pain and stiffness in patients with osteoarthritis, making it a promising and safe alternative treatment.^[41] Furthermore, studies have shown that bromelain has a positive effect on various forms of arthritis, including osteoarthritis and rheumatoid arthritis.^[33] When combined with other nutraceuticals like turmeric, bromelain enhances the therapeutic efficacy for degenerative joint pain conditions. These attributes make bromelain a viable dietary supplement alternative to non-steroidal anti-inflammatory drugs (NSAIDs). The analgesic properties of bromelain are attributed to its influence on pain mediators, particularly bradykinin. Clinical research has shown that bromelain is effective in reducing inflammation associated with arthritis and can lead to significant or complete reduction in soft tissue swelling. These findings highlight the potential of bromelain as a beneficial treatment option for managing arthritis related symptoms.^[41]

Other Uses

The potential utilization of pineapple peel as a nonpharmacological remedy in the form of processed food and instant beverages is noteworthy. One contributing factor to hypertension is the decrease in intracellular potassium levels within

the body. Pineapple consumption could address this by providing a rich source of potassium, as it stands out among fruits with a high potassium content. Research by^[42] illustrated that pineapple peel contains a potassium level of 938.48 mg/kg, surpassing the potassium content found in the flesh and core, which are measured at 485.28 mg/kg and 12.98 mg/kg, respectively. This outcome demonstrates that the peel contains a greater amount of potassium compared to the flesh and core. Additionally, pineapple by-products, specifically peels, can be employed in the production of vinegar through fermentation. This process involves the utilization of selected strains of acetic acid bacteria, including propionic bacterium *acidipropionici*, *panteo agglomerans*, and *pantea dispersa*. Chalchisa *et al.* demonstrated the feasibility of producing vinegar from pineapple peels by utilizing yeast (*Saccharomyces cerevisiae*) for the aerobic conversion of sugar to ethanol, followed by the oxidation of ethanol to acetic acid (vinegar) using various strains of acetic acid bacteria. This study highlights the potential to attain added value through the recycling or conversion of supposed waste materials into beneficial products.^[43] In addition to being consumed fresh, cooked, juiced, and preserved in various cuisines, pineapples serve other purposes as well. Pineapple leaves are used to create the textile fiber pina, which finds applications in wallpapers, furnishings, and more. While pineapple peels are commonly utilized as animal feed, they have also led to the development of novel products such as cereal bars, cakes, jellies, citric acid extraction, production of phenolic compounds, extraction of bromelain from stem and rind, creation of hydrogel from peel cellulose, and the generation of nanocellulose from leaf fibers.^[44]

Traditionally, pineapple peel waste (PPW) has been repurposed for animal feed or land fertilization, as well as a substrate for bio-ethanol production. The role of antioxidants or reducing agents is significant in both the healthcare sector and chemical industry. Consequently, exploring PPW as a potential natural antioxidant is intriguing due to its role as a reducing agent in the biosynthesis of metal nanoparticles. Research has demonstrated that aqueous pineapple extract can effectively facilitate the biosynthesis of metal nanoparticles, including silver and copper nanoparticles.^[45] While fruits are commonly utilized parts of the plant, other components such as the root, rhizome, leaf, cortex, and stem possess diverse nutritional and medicinal properties. Leaves, stems, and pineapple fruit have established significance in traditional medicine as potent antioxidants, antidiabetic agents, vermifuges, emmenagogues, and hypolipemic agents. They also play roles in various stages of wound healing and act as anti-oedematous and anti-inflammatory agents in soft tissue injury recovery. Moreover, they have applications in treating conditions like arthritis, hematoma, and necrotic tissue. The root and fruit are ingested or topically applied for their anti-inflammatory and proteolytic properties. In the Philippines, the root is used as an anti-helminthic agent and a decoction of the root is used to treat diarrhoea. Additionally, the fruit aids digestion and helps clear bronchial passages, making it useful for individuals with pneumonia and bronchitis.^[44]

Utilization of Pineapple Peels

It is foreseen that the leftover fruit and by-products have the potential for further industrial applications, such as fermentation and the extraction of bioactive elements. Many research studies have explored the repurposing of waste generated by industries like fruits, vegetables, dairy, and meat. In a similar vein, concerted efforts have been directed towards effectively utilizing waste derived from pineapples from various sources. For instance, waste materials from pineapple canning facilities have been repurposed as a substrate for producing valuable substances like bromelain, organic acids, and ethanol as summarized in Table 4<4>. This is due to their inherent capacity as sources of sugars, vitamins, and growth-promoting agents.^[4] The utilization of pineapple peel as a cost-effective raw material for the synthesis of fiber, organic acids, phenolic compounds, and bromelain has drawn the attention of researchers. Pineapple waste has been the subject of several research as a fermentable substrate, suitable nutrition for bacterial culture, and possibly also as a source of carbon for acid fermentation (45). The fermentation of sugars and other nutrients collected from pineapple waste might yield organic acids, single-cell proteins, enzymes, and bacterium cellulose. Several studies have confirmed that processing waste may be used as a novel, low-cost source of dietary fiber, phenolic antioxidants, pectin, proteolytic enzymes, organic acids, food additives, essential oils, and other nutrients by using different extraction, purification, isolation, and fermentation techniques. The extraction of antioxidant compounds from raw, oven-dried, and freeze-dried peels, including phenolic compounds, ferulic acid, vitamin A, vitamin C, vitamin E and carotenoids by using extraction techniques such as wet grinding, cold percolation, UV-C radiation and precipitation can be achieved (46). Using alkaline extraction and hydrothermal alkaline extraction techniques several enzymes like bromelain can be extracted by number of methods like precipitation, gemini surfactant based reverse micelle, and ATPS (Aqueous two-phase systems) (47). Furthermore, the extraction of fiber-rich fractions could be done using traditional techniques, cold percolation, wet grinding, UV-C radiation, and alkaline extraction. These fiber-rich fractions were studied for their relationship to polyphenols and possible uses, such as supplying carbon during fermentation, promoting the growth of lactic acid bacteria, bolstering probiotic yogurt with powdered pineapple peel, which is high in fiber, and boosting the amount of phenolic antioxidants in various products. Moreover, utilizing hydro-distillation, enzyme-assisted hydro-distillation, and supercritical fluid extraction techniques the extraction of oil and fatty acids from pineapple peel can be done (48).

Fruit peels and leaves, a waste product of the jam and juice industries, are rich in lignin and cellulose and provide an excellent raw material for related fibers. Utilizing pineapple waste for recycling instead of cotton or artificial fibers can reduce the amount of forest resources used, and it may be blended with other related fibers to enhance their quality and applications. In the agricultural sector, cellulosic natural fiber derived from pineapple leaves is seen as a more environ-

mentally friendly substitute for traditional polyethylene (PE) soil cover. The usage of soil covers made of pineapple leaf fibers could reduce the issue with disposing of traditional plastic coverings, which takes hundreds of years to breakdown (49).

During the past ten years, using pineapple wastes to produce bioethanol has become a significant valorisation technique. The two main benefits of producing ethanol from pineapple cannery wastes are the low cost of ethanol production and the resolution of the pineapple waste disposal issue. Additionally, respiration-deficient strain *Saccharomyces cerevisiae* has been employed to continuously produce ethanol from the squeezed juice of pineapple cannery waste.^[5] The essential oil found in pineapple peel and leaves is composed of alcohols (18%), esters (35%), ketones (26%), aldehydes (9%), acids (3%), and miscellaneous chemicals (9%). Pineapple essential oils are readily accessible on the market, providing a mild pineapple aroma that is commonly utilized in the manufacturing of body lotions, bath salts, scented candles, and other personal care items. One of the most popular tastes is vanilla, which is mostly made of vanillin (4-hydroxy-3-methoxybenzaldehyde), which is derived from vanillic acid. The fermenting pods of vanilla orchids (*Vanilla planifolia*) are the source of natural vanillin. Alternative methods, such as biotechnology and fermentation and enzymatic reactions, such as an enzymatic manufacturing technique, have also been documented for the production of vanillin. Ferulic acid, a precursor to vanillic acid, is found in leftover pineapple peel. Therefore, microbial biological transformation is used in the manufacturing process to produce vanillin from pineapple waste (53).

Studies have been conducted on the extraction and purification of bromelain; however, due to limitations arising from the laboratory-scale nature of most methods, manufacturing prices have increased. Scientists are putting a lot of effort into understanding the distinctive qualities that distinguish compounds like bromelain in their endeavour to purify these biomolecules. The idea is to develop a technique for removing a particular molecule from a mixture in which all of the constituents share the same fundamental characteristics. For the past twenty years, researchers have focused on the purification of bromelain. Their focus has been on figuring out how to extract bromelain from various pineapple components. Using ATPS, a technique where the target molecule is segregated into one phase owing to differences between a polymer solution and a salt solution, is one important strategy they have investigated. As a result, the molecule is kept in a stable environment that permits purification without sacrificing its biological function. In order to increase process efficiency of bromelain extraction, a study examined variables such as pH and component concentrations (potassium phosphate and polyethylene glycol). Another study employed a similar technique in a micro column to explore continuous enzyme recovery, and the purified protein content and biological activity showed encouraging findings. Researchers have investigated the circumstances under which ethanol may be used as a precipitant to precipitate bromelain from crude extracts (51). Although this approach results in protein precipitation, difficulties regulating temperature when adding ethanol have rendered it less

desirable. The overall goal of the research is to identify economical and effective methods for purifying bromelain without compromising its biological activity (52).

Conclusions

Pineapple peel, often discarded as waste, holds significant pharmacological properties and health benefits. Studies have shown that pineapple peels can aid digestion, reduce symptoms of irritable bowel syndrome (IBS), alleviate constipation, and combat intestinal parasites. They also promote a healthy gut flora. These products can have various applications, such as the development of dietary supplements, functional foods, and natural remedies. Pineapple peels are rich in bioactive compounds, including antioxidants, phenolics, flavonoids, and dietary fibre, which contribute to their therapeutic potential. Harnessing the pharmacological properties of pineapple peel not only helps reduce waste but also offers a sustainable and cost-effective solution for improving health and well-being. By recognizing the untapped potential of pineapple peel, we can unlock its numerous benefits and contribute to a more sustainable and circular economy.

Author Contributions

M.M., F.F and S.Q.D wrote the main manuscript, along with reviewing and editing all figures and tables while S.D., A.W.W and A.F participated in review, data curation and supervision throughout the writing process. S.K and A.K.W framed the references, editing and formatting of manuscript. All authors reviewed the manuscript.

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Conflict of Interests

The authors declare no conflict of interest.

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