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**Recent Advances and Strategies for the Valorization of Pineapple Waste in Sustainable Bioeconomy Applications**

# ABSTRACT

Pineapple processing produces considerable agro-industrial waste, comprising peels, cores, crowns, and stems, which presents environmental issues while simultaneously providing enormous prospects for sustainable use. These by-products, abundant in bioactive substances including bromelain, phenolic acids (e.g., ferulic, gallic), flavonoids, and dietary fiber, provide significant value for several industries, including food, medicines, cosmetics, and bioenergy. This study examines current progress in the extraction, characterisation, and application of these chemicals, highlighting solutions consistent with circular bioeconomy concepts. The valorization of pineapple waste mitigates environmental degradation and reliance on landfills while simultaneously increasing economic returns through the creation of high-value products. This analysis provides scalable, environmentally sustainable ideas pertinent to both developing and developed economies, in light of the increasing worldwide focus on sustainable development and resource efficiency.

# KEY WORDS

Pineapple, Pineapple waste, Bioactive compounds, and Waste utilization

# INTRODUCTION

**Pineapple**

Fruits and vegetables are among the most commonly consumed foods, valued for their health benefits due to the presence of antioxidants, dietary fiber, essential vitamins, and minerals. These natural compounds, known as phytochemicals, are known to lower the risk of conditions like cardiovascular diseases and obesity. However, the increasing preference for processed and packaged foods has led to a rise in fruit and vegetable processing, which in turn generates a significant amount of waste. Countries such as the United States, India, the Philippines, and China are among the leading producers of this type of waste, generating approximately 15.0, 1.8, 6.5, and 32.0 million tonnes, respectively. A considerable portion of fruit waste originates at the farm level and forms a major part of the overall waste generated. Some processing units attempt to reduce this impact by utilizing waste to produce biogas or converting it into organic compost. However, managing fruit-processing waste often demands substantial financial investment, with transportation expenses accounting for a large share of the cost. Among the commonly used disposal methods is landfilling, though it poses environmental challenges, including the emission of greenhouse gases (FAO, 2013) (Banerjee et al., 2018).

Pineapple (*Ananas comosus*) is a globally significant fruit and is the most widely consumed species within the Bromeliaceae family (Upadhyay et al., n.d.). Pineapple is the only species from its family that is cultivated on a commercial scale for fruit production and is highly valued for its nutritional benefits. This tropical, perennial fruit plant is widely recognized across the globe. Originating in South America, pineapple

cultivation eventually spread to various regions around the world. Today, it ranks as the third most consumed fruit globally, following bananas and citrus fruits (Abraham et al., 2023). Pineapple juice ranks third in global preference, following orange and apple juices. The plant typically grows to a height of 75 to 150 cm and spreads about 90 to 120 cm. It has a compact structure with a thick central stem and long, narrow, fibrous leaves that are often spiny. As it matures, the plant produces a cone-shaped, fleshy, and juicy fruit topped with a leafy crown (Upadhyay et al., n.d.).

This tasty tropical fruit can be enjoyed in multiple forms, including as dried slices, canned products, juices, jams, and other processed items (Abraham et al., 2023). Pineapple-based products such as jams and concentrates are in high demand in international markets. The leading producers of pineapples include Costa Rica, Brazil, the Philippines, India, Thailand, and Indonesia, with respective production volumes of 2.93, 2.69, 2.61, 1.96, 1.81, and 1.39 million tonnes, according to FAOSTAT (2016). Globally, the most commonly cultivated varieties are Smooth Cayenne, Abacaxi, Red Spanish, and Queen. Smooth Cayenne is recognized for its smooth skin and is ideal for canning. Abacaxi produces long fruits with juicy, translucent white flesh, and although it is considered the most flavorful, its delicate nature makes it unsuitable for canning. The Queen variety is compact and dwarf-like with a rough exterior, while Red Spanish features fruits and foliage with a purplish hue. Beyond these, numerous hybrid varieties of pineapple are also cultivated around the world (Banerjee et al., 2018).

Pineapple is packed with essential nutrients, including vitamins, bromelain, β-carotene, dietary fiber, manganese, copper, calcium, and zinc. Moreover, its pulp is naturally free of cholesterol and fat, and it is low in sodium and calories (Abraham et al., 2023). Pineapple is also known for its antioxidant content, including carotenoids, ascorbic acid (vitamin C), and flavonoids. However, the specific chemical makeup of the fruit can differ depending on the variety and region where it is grown. A single fresh pineapple can provide around 17% of the recommended daily intake of vitamin C and is also a good source of B-complex vitamins such as pyridoxine, folate, riboflavin, and niacin. The fruit contains bromelain, an enzyme recognized for its anti-inflammatory, anti-cancer, and anti-clotting effects. On average, 100 grams of fresh pineapple delivers about 86.45 grams of water, 48 kilocalories, 12.66 grams of carbohydrates, 9.35 grams of total sugars, and

1.4 grams of dietary fiber. It also supplies essential minerals like potassium (151.5 mg), magnesium (16.5 mg), calcium (13 mg), and phosphorus (11 mg). Additionally, pineapple is rich in vitamins C (36.5 mg) and A, along with smaller amounts of vitamins B6, D, E, K, folic acid, thiamine, and riboflavin (Sukri et al., 2023). Including pineapple in the diet offers several health benefits, such as boosting the immune system, aiding in protein digestion, easing symptoms of the common cold, and promoting bone health. Thanks to its rich nutritional profile, pleasant texture, and appealing flavor, pineapple is suitable for consumption across all age groups (Abraham et al., 2023).

**Pineapple Waste**

Pineapples generate significant waste during field harvesting, post-harvest processes, and through domestic consumption (Paz et al., 2024). Global pineapple production reaches approximately 16 to 19 million tons annually, with plantation areas covering around 920,349 hectares (FAO, 2007). This results in an estimated total production of over 18 million tons. The large-scale production of pineapples and their by-products leads to the generation of significant amounts of waste (Roda et al., 2019). Improper handling of fruits and exposure to unfavorable environmental conditions during transportation and storage can lead to significant product loss, with up to 55% of pineapples being wasted. The drying, storage, and shipment of these

by-products are considered cost-effective, making it increasingly important to find efficient, affordable, and environmentally-friendly methods for their utilization. While high-quality pineapples are selected for shipping, the majority are either consumed fresh or processed into canned products. Lower-quality fruits, however, often do not meet market standards and are left on farms. Additionally, large amounts of waste are generated during pineapple processing. Studies indicate that between 40% and 80% of the fruit is discarded as waste, which is rich in biological oxygen demand (BOD) and chemical oxygen demand (COD) (Upadhyay et al., n.d.). During industrial processing, the pineapple's stem and crown are removed, leaving only the pulp after the shell and core are discarded. This residual material, which accounts for around 50% of the fruit's mass, is becoming an environmental concern due to its susceptibility to microbial deterioration. Additionally, other parts of the plant, such as the stem, roots, and leaves, are often discarded in the fields as agricultural waste, contributing to significant waste generation (Lima et al., 2018). The generation of waste from pineapple processing varies depending on the part of the fruit involved. Specifically, pineapple peels contribute to 30% to 42% of the by-products, while the core accounts for around 10% by weight. Ideally, the core and stem should make up no more than 5% of the total waste weight. In total, approximately half of the pineapple's weight ends up as by-products, which could be a potential source of valuable compounds (Roda et al., 2019).

**Crown**: This by-product can make up 25-30% of the fruit's total weight. Typically, it is replanted for the next harvest (Polanía et al., 2023). The pineapple crown contains various elements, including carbon (39.52%), hydrogen (5.51%), nitrogen (13.82%), and sulfur (0.46%). It also contains fructose (0.82 ± 0.05%), glucose

(0.53 ± 0.02%), pulp (2.41 ± 0.05%), a pH of 3.94, total soluble solids (1.51%), and acids (0.32%) (Nath et al., 2023). Cellulose nanocrystals were extracted from pineapple fibers derived from crown waste through chemical treatments and acid hydrolysis. This process followed the removal of non-cellulosic compounds via bleaching and mercerization. The resulting cellulose nanocrystals demonstrated potential for reinforcing polymeric nanocomposites, materials designed to enhance the surface properties of substrates for various applications (Vieira et al., 2022). An alkaline pretreatment of pineapple crowns leads to the production of ferulic acid, which can be converted into vanillic acid by *Aspergillus niger*. Vanillic acid is an important precursor in the production of vanilla and other industrial derivatives. Additionally, pineapple crowns have shown potential as an economical bio-adsorbent for treating wastewater by removing chromium ions (Cr VI and Cr III) from the aqueous phase (Nath et al., 2023).

**Stem/core:** Bromelain is commonly extracted from the pineapple stem. After separating the starch from the stem, its properties were compared with those of starches from other sources such as cassava, rice, and corn. In an enzymatic hydrolysis process, sugarcane bagasse, treated with hydrogen peroxide, was further broken down using cellulase, xylanase, and pineapple stem juice, which contains a mixture of proteases and esterases as co-adjuvants. The study revealed that the enzymatic hydrolysis process reduced the amount of cellulase needed, as the enzymes from the pineapple stem juice enhanced the breakdown of lignocellulosic linkages, thereby increasing the production of glucose and cellobiose from the bagasse (Vieira et al., 2022). The study found that pineapple stem starch differs from industrial starches in its resistance and thermoplastic properties, offering potential applications in both food and non-food industries. The effects of microwave drying on the ascorbic acid content and proteolytic enzyme activity in pineapple by-products (stem and core) were tested at different power levels (380W, 530W, and 680W). Increasing the power from 380W to 530W significantly improved ascorbic acid retention. Pineapple core, which makes up 15% of the total pineapple processing waste, is rich in bromelain enzyme. It also contains higher levels of glucose and fructose

compared to the peel and crown, which could be beneficial for fermentation processes producing citric acid and other products. The highest ascorbic acid content (0.85 mg/100 mL) was found in the core dried at 530W, while the stem dried at 680W had the lowest content (0.68 mg/100 mL). The pineapple core, dried at 380W, showed the highest proteolytic enzyme activity (0.0038 U/mL), followed by the stem (0.0023 U/mL). Ascorbic acid, an important water-soluble vitamin, is essential for preventing and treating scurvy and serves as an antioxidant, with additional health benefits. These findings suggest that pineapple by-products could be valuable in producing citric acid and other products. The stem also showed potential as a cost-effective adsorbent for removing methylene blue dye from aqueous solutions, highlighting its usefulness as a dye remover. Furthermore, the stem and peel of the pineapple can be processed into prebiotic functional flours, which produce phenolic compounds with strong antioxidant properties during digestion. Additionally, pectinase, another enzyme found in pineapple, has significant market value and is widely used in the food and textile industries (Nath et al., 2023).

**Peels:** Among the various by-products from pineapple processing, the peel has numerous potential applications. Pineapple peels are rich in bioactive compounds and serve as the second-largest source of bromelain, following the fruit's crown (Nath et al., 2023). The antioxidant potential of pineapple peel is attributed to its primary phenolic compounds—gallic acid, epicatechin, catechin, and ferulic acid—which have the ability to neutralize free radicals linked to various diseases (Vieira et al., 2022). Proximate analysis indicates that 100 grams of dried pineapple peels contain 5.1 grams of crude protein, 5.3 grams of lipids, 4.3 grams of ash, and 55.5 grams of carbohydrates. Due to their high carbohydrate content, these by-products offer significant potential as raw materials for biogas production (Polanía et al., 2023). In the food manufacturing industry, researchers are exploring the production of vinegar from pineapple peel waste, developing prebiotic flour and cereal bars, and incorporating nitrogen sources to boost protein yield, making it suitable for use as livestock feed (Nath et al., 2023). Pectin can be extracted from pineapple peels and used to create biopolymers (Vieira et al., 2022).

**Pomace**: Pineapple pomace, which contains higher levels of fiber and vitamin C than carrot pomace, makes an excellent ingredient for producing bread with enhanced nutritional value (Vieira et al., 2022). Polysaccharides can be isolated from pomace, and these have the potential to act as hypoglycemic agents in both biomedical applications and functional foods. Due to its high fiber content, bioactive compounds, and low fat, this waste can be utilized in extrusion-based foods that have a higher glycemic index and lower nutritional value (Nath et al., 2023).



CROWN PEEL CORE


# FIGURE 1

**This figure represents Pineapple and it’s various parts (Crown, Peel and Core) typically regarded as waste fractions**

**Bioactive compounds**

"Bioactive compounds" refers to molecules with biological activity, such as secondary metabolites found in plants, which can have pharmacological effects on both animals and humans, offering potential health benefits. Pineapple waste may contain valuable bioactive substances with various therapeutic properties, including antibacterial, anti-inflammatory, and antioxidant effects. These benefits may be attributed to bioactive metabolites such as pigments, sugars, organic acids, amino acids, and the proteolytic enzyme bromelain (Azizan et al., 2020). For instance, citric acid is found in pineapple leaves, while bromelain is present in the stem, leaves, and peel of the fruit. Ferulic acid is also found in the leaves, ascorbic acid is in the core, and other bioactive compounds are distributed throughout the plant. Additionally, bioactive polyphenolic compounds, due to their biological properties and potential applications, play a key role in the pharmaceutical and dietary supplement industries. Pineapple waste contains several of these antioxidants, such as myricetin, salicylic acid, tannic acid, trans-cinnamic acid, and p-coumaric acid (Dhar et al., 2023). The high dietary fiber powder derived from pineapple shell waste contains antioxidants. The polyphenols found in pineapple waste, such as ferulic acid and syringic acid, have demonstrated antioxidant and antibacterial properties (Nath et al., 2023).

Starch

Milling pineapple agro-wastes (PAWs), particularly stem waste, enables the extraction of starch. The starch isolated from pineapple stems has higher amylose content (34.5%) compared to rice, corn, and cassava starches. This content is more than double that of maize, over double that of cassava starch (15.7%), and five times that of rice (6.3%). As a result, pineapple stem starch exhibits the highest solubility, exceeding 32% (Nath et al., 2023). Pineapple starch exhibits the lowest viscosity when cooked under standard circumstances. The pineapple starch's numerous culinary uses as a resistant and thermoplastic starch have been validated by all of these characteristics and quirks (Roda et al., 2019).

Dietary Fibre

Dietary fiber (DF) is a crucial component of a healthy, nutrient-rich diet. Despite the recommended daily intake being 38 grams for men and 25 grams for women, the average daily intake is only about 15 grams. A growing number of individuals are dealing with overweight issues, and nearly 2 billion people lack sufficient micronutrients in their diet. With the global population projected to increase by 2 billion over the next 30 years, reaching 9.7 billion, there is a growing interest in exploring fruit and vegetable waste (FVW) as an alternative source of dietary fiber. This approach could help address the challenge of waste disposal while also meeting the dietary needs of a rapidly growing population (Khanpit et al., 2021). The food industry increasingly utilizes dietary fiber with beneficial nutritional and physicochemical properties, often sourcing it from the fiber-rich parts of agricultural byproducts to enhance functional foods (Roda et al., 2019). This waste fiber matrix exhibits various functional properties, such as swelling capacity, water-holding ability, gel formation, and cation exchange capacities. Pineapple waste, which contains both soluble and insoluble fiber-rich fractions, holds significant potential for use in producing low-calorie, high-fiber foods (Dhar et al., 2023). Researchers have identified fibers derived from pineapple fruit. Studies indicate that dietary fiber powder from pineapple shells has enhanced sensory properties and contains 70.6% more total dietary fiber compared to commercial fibers sourced from citrus and apple fruits (Nath et al., 2023). Pineapple waste contains fiber-rich fractions that can be used as functional ingredients to improve texture, water retention, and other properties in food products such as sauces, dressings, and meat items. The microfiber and nanofiber extracted from pineapple leaves exhibit exceptional mechanical properties due to cellulose, which benefits from intra- and intermolecular hydrogen bonding. These fibers hold potential for creating biocomposite materials. They could be incorporated into matrix materials, both natural and synthetic polymers, to enhance their mechanical properties (Dhar et al., 2023). Researchers found that the mechanical properties of composites made from pineapple fibers surpass those of other natural fiber composites derived from cellulose. In several Southeast Asian countries, pineapple leaves have been traditionally used to produce coarse fabrics and threads. Alkaline pulping methods, with yields of less than 40%, were found to be more effective than semi-chemical mechanical pulping. It was also noted that 2.1g of fiber can be extracted per 100g of pineapple pulp waste (Upadhyay et al., n.d.).

Although the potential uses of pineapple leaf fibers in the food industry are limited, their mechanical properties and natural characteristics make them suitable for specific applications, such as edible films and coatings, natural food coloring, and prebiotic fibers. Pineapple waste fibers exhibit various properties, including texture, length, water-holding capacity, dye retention, brightness, whiteness, salt resistance, and tensile strength. The dietary fibers extracted from pineapple waste have diverse applications as prebiotics, food additives, and bio-preservatives. Additionally, pineapple peel flour can serve as an excellent alternative to other raw materials in the production of cereal bars, as it contains significant amounts of crude fiber, thereby boosting the nutritional content of the final product. Incorporating fruit peel flour into food items

helps achieve two main goals: improving texture and offering health benefits, such as lowering the glycemic index and supporting weight management (Dhar et al., 2023).

Phenolic Antioxidant

In recent years, there has been considerable growth in the search for new natural antioxidants. Agro-industrial waste is being explored as a resource for this research, with one of the driving factors being the low cost of these wastes, which would otherwise be discarded as environmental waste (Dhar et al., 2023). Phytochemicals, particularly phenolic compounds, found in fruits and vegetables are believed to be the primary bioactive substances responsible for their health benefits (Upadhyay et al., n.d.). These compounds are the by-products of the plant’s metabolic processes (Dhar et al., 2023). The chemistry of phenolic compounds, including their antioxidant activity, occurrence in different foods, bioavailability, and metabolism, has been explored. Several studies have reported on the phenolic content of pineapple (Upadhyay et al., n.d.). Research into the phytochemicals present in pineapple peel and leaves is ongoing, but studies have already shown that these parts contain significant amounts of phenolic compounds and exhibit antioxidant activity. The leaves, in particular, are rich in phytosterols such as beta-sitosterol, stigmasterol, and campesterol. Furthermore, the highest yield of phenolics from pineapple agro-processing by-products (PAPs) was achieved in 30 minutes using 75% ethanol at 75°C. Different extraction methods also resulted in varying yields of total phenolic content (TPC) (Nath et al., 2023). The methanolic extraction of pineapple waste, including peel, seeds, and pulp, resulted in a yield of 30.2%, with a total phenolic content of 10 mg/g GAE (Dhar et al., 2023). The juice contained 358 mg/L of gallic acid equivalent, while the fruit had 40.4 mg/100g of gallic acid equivalent, with the highest ethyl acetate-bound phenolic content measured at 2.58 as chlorogenic acid equivalent. It was observed that the extraction methods used in different studies vary, and the phenolic content extracted is influenced by the solvent concentrations employed (Upadhyay et al., n.d.). The fruit was extracted using 80% acetone, followed by base digestion and extraction with ethyl acetate. The entire extract was then centrifuged before measuring the total phenolic content. Extraction of crude polyphenols using aqueous methanol, ethanol, or acetone is a common and widely used method (Dhar et al., 2023). It has been found that 50% acetone and 70% ethanol are the most effective solvents for extracting phenolic compounds (Upadhyay et al., n.d.). Hexane extraction is sometimes carried out before ethyl acetate extraction to concentrate highly polar compounds. The dichloromethane extract from pineapple stem and leaf phenolic components could serve as a viable, sustainable source of natural antioxidants (Nath et al., 2023)It has been found that these wastes are rich in phenolic antioxidants. Pineapple shell powder, which is high in dietary fiber, contains phenolic compounds such as myricetin, salicylic acid, tannic acid, trans-cinnamic acid, and p-coumaric acid. Reports indicate that pineapple peel has a FRAP value of 2.01 mmol/100 g of wet weight. Furthermore, the leaves contain a significant amount of phytosterols, including beta-sitosterol, stigmasterol, and campesterol (Upadhyay et al., n.d.).

Organic Acids

The fermentation process typically transforms the free sugars in fruits into various organic acids. Given that pineapple waste is rich in sugar, it serves as an ideal substrate for organic acid production (Nath et al., 2023). Pineapple by-products are valuable in both the food and pharmaceutical industries. They have also been explored as cost-effective substrates for fermentation processes that yield organic acids such as citric, ferulic, and lactic acids (Banerjee et al., 2022). Pineapple waste from industrial processes primarily consists of sucrose, glucose, fructose, and other nutrients. If these wastes are not treated before being released into the

environment, they can lead to significant environmental issues. However, these by-products can be recycled into raw materials or converted into valuable products like organic acids. This approach not only reduces the potential environmental harm but also adds value. Organic acids have been widely used in various industries, including food, chemicals, cosmetics, and pharmaceuticals (Nath et al., 2023).

* Ferulic Acid (FA)

Ferulic acid is a prominent hydroxycinnamic acid commonly found in the cell walls of plants (Upadhyay et al., n.d.). It is abundant PAP and crown leaves and is extensively accessible in the local agricultural industry. It is covalently bonded to lignin and polysaccaharides in plant cell walls by ether or ester linkages and polysaccharides, respectively. It must be produced by extraction from natural sources and chemical synthesis (piperidine and vanillin condensation process catalyzed by malonic acid). It is abundant in PAP and crown leaves and is extensively accessible in the local agricultural industry. It is covalently bonded to lignin and polysaccharides in plant cell walls by ether or ester linkages and polysaccharides, respectively. It must be produced by extraction from natural sources and chemical synthesis piperidine and vanillin condensation process catalyzed by malonic acid (Nath et al., 2023). This phenolic antioxidant is widely used in the food and cosmetic industry. Pineapple peel has been used for the alkali extraction of ferulic acid(Upadhyay et al., n.d.).

Ferulic acid can also be obtained from sources like rice bran and wheat bran, typically through alkaline extraction methods. In the food industry, it serves multiple purposes including acting as a natural preservative and flavor enhancer, primarily due to its strong antioxidant activity. When incorporated into products like bread, cereals, and snacks, it can boost nutritional value. Additionally, ferulic acid is gaining attention in the creation of biodegradable packaging materials such as films and coatings. These materials not only extend food shelf life but also offer an eco-friendly alternative to synthetic preservatives. In pharmaceuticals, ferulic acid is being explored for its health-promoting effects, with studies highlighting its anti-inflammatory, anti-carcinogenic, and neuroprotective potential. This makes it a valuable compound across sectors like food, medicine, and cosmetics (Dhar et al., 2023).

* Citric Acid (CA)

The food, pharmaceutical, and beverage industries frequently use this economically valuable substance as a substrate to improve flavor and acidify meals(Upadhyay et al., n.d.). The food business uses around 75% of CA economically, whereas the pharmaceutical industry uses 12% (Nath et al., 2023). Several studies have explored the use of pineapple waste, particularly residues from juice extraction, as a substrate for producing citric acid through solid-state fermentation using *Aspergillus niger* (Upadhyay et al., n.d.). Additionally, methanol was observed to enhance citric acid production during solid-state fermentation, increasing yields from 37.8% to 54.2%. In these experiments, pineapple waste was used as the fermentation substrate, and the yeast *Yarrowia lipolytica* was employed to produce citric acid`(Dhar et al., 2023). Following the optimization of cultivation conditions, a yield of 202.35 g/kg of dried pineapple waste was obtained for citric acid production. In a separate investigation, wet pineapple waste was also utilized as a fermentation substrate. When using *Aspergillus foetidus* ACM 3996 in solid-state fermentation, citric acid yields were found to be superior compared to those derived from other agro-industrial residues such as rice bran, wheat bran, or apple pomace. Another comparative study involving four species of *Aspergillus* demonstrated that, under optimal conditions, up to 19.4 g of citric acid could be produced per 100 g of dry fermented pineapple waste

(Upadhyay et al., n.d.).

While pineapple waste is not the primary raw material for citric acid production, it presents a viable alternative substrate. The global production of citric acid is largely driven by microbial fermentation using *Aspergillus niger*, a filamentous fungus known for its high citric acid yield. However, the citric acid concentration in pineapple waste tends to be lower compared to other agricultural sources such as citrus fruits (e.g., oranges and lemons) and sugarcane molasses. Despite this, the feasibility of using pineapple waste depends on several factors, including the cost of production, availability of raw materials, and market demand. Therefore, selecting a suitable feedstock for citric acid production requires consideration of economic viability, local resource availability, and process-specific needs (Dhar et al., 2023).

* Lactic Acid (LA)

Lactic acid (LA) plays a crucial role in both food and non-food industries due to its versatile applications. In the food sector, it is commonly used as a preservative and acidulant (Nath et al., 2023). The commercial production of lactic acid can be costly due to the raw materials used, particularly the exploitation of biological waste. Some researchers have explored using pineapple syrup, a by-product of food processing, as an affordable substrate for lactic acid production. They utilized Lactobacillus lactis and the enzyme invertase to break down sucrose into glucose and fructose. Additionally, lactic acid has been produced through a 72-hour anaerobic fermentation process using pineapple liquid waste as the substrate with Lactobacillus delbrueckii (Dhar et al., 2023). By employing calcium alginate as the immobilization matrix, the maximum lactic acid production achieved was between 0.78 and 0.82 grams of lactic acid per gram of glucose, across various pH and temperature conditions (Nath et al., 2023). The fungal production of lactic acid from pineapple waste yielded 19.3 g/L with *Rhizopus arrhizus* and 14.7 g/L with *Rhizopus oryzae* (Upadhyay et al., n.d.).

Bromelain Enzyme

Bromelain, a key component derived from pineapple waste, is likely the most valuable and studied. This crude extract contains several closely related proteinases, which have demonstrated antiedematous, anti-inflammatory, antithrombotic, fibrinolytic, and potentially anticancer effects, as shown in both in vitro and in vivo studies (Upadhyay et al., n.d.). Among its many uses are the production of protein hydrolysates, baking, brewing, and meat tenderization. The enzyme bromelain was even utilized in traditional medicine to cure wounds, lessen inflammation, prevent diarrhea, and improve digestion (Dhar et al., 2023). The main proteases present in the crude enzyme mixture, stem bromelain (EC 3.4.22.32) and fruit bromelain (EC 3.4.22.33), are both sourced from pineapple plants (Nor et al., 2015). Bromelain plays a key role in various situations and supports the digestive process in the body (Nath et al., 2023). Bromelain is primarily found in pineapple stems (EC 3.4.22.32) and fruit (EC 3.4.22.33), with trace amounts also present in other parts of the pineapple, including the peel, core, and crown. Researchers have used reverse micellar systems to extract and purify bromelain from a crude aqueous extract of pineapple waste materials. The efficiency of extracting this proteolytic enzyme from pineapple has been compared with the extraction of papain from papaya. Unlike papain, bromelain remains intact as the pineapple fruit matures. Techniques such as ammonium sulfate fractionation, gel filtration, and ion-exchange chromatography have been employed to purify bromelain from pineapple stems. In recent advancements, metal affinity membranes and aqueous two-phase systems have also been utilized for bromelain purification from crude extracts. Processing under severe sterilizing,

precipitation, and auto-digestion conditions lowers bromelain's proteolytic activity, which lessens its therapeutic benefits. Therefore, there has always been interest in the stability of bromelain. Better thermal stability was achieved by immobilizing stem bromelain using the metal affinity support's lone histidine. Bromelain's thermal stability was improved following its complexation with tea polyphenols. However, when fruit bromelain was stored at -4oC for 180 days, its natural stability was maintained to about 80% even without the addition of preservatives (Upadhyay et al., n.d.).

# TABLE 1

**This table represents bioactive compounds derived from pineapple waste, their properties and applications**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Bioactive Compound** | **Source in Pineapple Waste** | **Key Properties** | **Applications** | **References** |
| Bioactive Compounds | Leaves, stem, peel, core | Antibacterial, anti-inflammatory, antioxidant (e.g.,bromelain, ferulic acid) | Pharmaceuticals, dietary supplements, functional foods | (Azizan et al., 2020; Dhar et al., 2023) |
| Starch | Stem | High amylose (34.5%), low viscosity,thermoplastic properties | Resistant starch, food thickener,biodegradable packaging | (Nath et al., 2023; Roda et al., 2019) |
| Dietary Fiber | Peel, core, leaves | High water-holding capacity, gel formation, prebiotic effects | Low-calorie foods, meat products, edible films, cereal bars | (Dhar et al., 2023; Khanpit et al., 2021) |
| Phenolic Antioxidants | Peel, leaves, stem | High antioxidant activity (e.g., ferulic acid, myricetin, tannic acid) | Natural preservatives, nutraceuticals,cosmetics | (Upadhyay et al., n.d.; Nath et al., 2023) |
| Organic Acids | Fermented waste (peel, core) | Citric, ferulic, and lactic acids | Food acidulants, preservatives,pharmaceuticals | (Banerjee et al., 2022; Nath et al., 2023) |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Ferulic Acid (FA) | Leaves, crown | Antioxidant, anti-inflammatory, bound to cell walls | Food preservatives, biodegradable packaging, cosmetics | (Dhar et al., 2023; Upadhyay et al., n.d.) |
| Citric Acid (CA) | Fermented peel/juice residue | Flavor enhancer, acidulant | Beverages, pharmaceuticals, cleaning agents | (Upadhyay et al. n.d.; Nath et al., 2023) |
| Lactic Acid (LA) | Fermented liquid waste | Preservative,biodegradable polymer precursor | Food industry, bioplastics (PLA) | (Nath et al., 2023; Dhar et al., 2023) |
| Bromelain Enzyme | Stem, fruit, peel | Proteolytic, anti-inflammatory,fibrinolytic | Meat tenderizing,digestive aids, wound healing,pharmaceuticals | (Nor et al., 2015; Upadhyay et al., n.d.) |

**Applications of pineapple waste**

Animal Feed

The production of animal feed has emerged as a growing industry, and the use of agro-industrial by-products, such as pineapple waste, offers a solution to the challenges of forage shortages during critical periods. Research has increasingly focused on the potential of utilizing pineapple waste as feed for ruminants. Due to its content of sugars, fiber, and organic acids, pineapple waste can be processed into valuable, long-lasting products suitable for animal nutrition (Kamusoko et al., 2025). Pineapple by-products, such as the leaves, outer peel, skin, and core from canning processes, are being utilized as feed for ruminants. Studies have examined the digestion and performance of these pineapple by-products in animal feed. Over an 80-day period, crossbred goats showed an increase in weight, and the digestibility of dried pineapple by-products was found to improve during this time (Nath et al., 2023). In Brazil, female goats are sometimes fed a mixture of dried pineapple by-products in place of 100% Cynodon dactylon straw. This substitution has been shown to improve nutrient digestion and promote expected weight gain. Depending on the specific needs of the livestock, pineapple waste, including leaves (crowns) and stems, can be processed and blended with other feed ingredients to create pellets suitable for birds and other animals, including ruminants. When used in the diets of dairy animals, the high fiber content in pineapple leaf waste can contribute to increased milk production (Wulan et al., 2022). In China, pineapple waste, either from the field or the cannery, is utilized as feed for dairy cattle. Cattle tend to prefer fermented pineapple waste with higher acidity over fresh waste. Both dried and ensiled pineapple waste can serve as supplemental roughage, potentially replacing up to 50% of the roughage in the total mixed ration for dairy cattle. In Nigeria, a survey indicates that pineapple waste is also used to feed small ruminants, provided it undergoes proper processing. Additionally, there are reports on

the use of pineapple waste for animal feed, as well as the potential for pulp to be used for human consumption (Upadhyay et al., n.d.). Several studies have noted that the high fiber and low protein content of pineapple processing by-products make them unsuitable for direct use in animal feed (Nath et al., 2023).

Single Cell Protein (SCP)

In response to the global protein shortage, single-cell proteins (SCPs), also referred to as microbial proteins derived from fruit wastes, have gained increasing attention as an affordable and reliable protein source. The idea of using microorganisms as a food source is not recent; for centuries, people have consumed microorganisms in the form of fermented foods such as bread, wine, alcoholic beverages, beer, sake, cheese, yogurt, and soy sauce (Thiviya et al., 2022). Several studies have demonstrated that pineapple waste can be utilized as a substrate for the production of single-cell proteins (SCP). The sugar-rich wastewater from pineapple canning operations has been employed as a substrate in SCP synthesis. These microbial proteins offer an affordable way to enhance the protein content in the diet of both humans and animals. SCP production occurs through the fermentation of pineapple agro-waste in solid, semi-solid, or liquid forms, using various microorganisms such as *Candida utilis*, *Saccharomyces cerevisiae*, *Aspergillus niger*, *Phanerochaete chrysosporium*, *Panus tigrinus*, *Rhizopus oligosporus*, and *Lactobacillus* species. By providing low-cost protein sources, the use of pineapple waste in SCP production not only helps mitigate environmental pollution but also contributes to addressing malnutrition (Nath et al., 2023).

Vinegar Production

Pineapple peels, being an excellent source of sugar, may serve as an ideal substrate for fermentation. This offers potential for producing vinegar from pineapple fruit through the conversion of sugars into acetic acid and alcohol (Roda et al., 2019). Pineapple agro-industrial by-products (PAP) can be transformed into vinegar through the simultaneous action of *Saccharomyces boulardii* and *Acetobacter*. The resulting vinegar has been shown to have phytochemical properties and antioxidant activity. A comparative study revealed that vinegar made from PAP exhibited stronger antioxidant effects (2.077 g acetate equivalent/100 mL) than vinegar derived from other fruit wastes. This product, with its therapeutic advantages and environmentally friendly nature, presents a promising alternative to synthetic vinegar for mass production and commercial use. Additionally, vinegar made from PAWs can be applied in various sectors, including as disinfectants, food dressings, and preservatives (Nath et al., 2023). A newly isolated thermotolerant acetic acid bacterium (TH-AAB) that demonstrates tolerance to both ethanol and acetic acid has proven to be highly effective in producing vinegar from pineapple peels. This bacterium offers a cost-effective, alternative raw material for vinegar production through simultaneous vinegar fermentation (SVF). Research indicated that, with an initial pH of 5.5 and the addition of diammonium phosphate (DAP) and magnesium sulfate (MgSO4), the whole pineapple peel produced slightly more acetic acid compared to juice-based fermentation (Fouda et al., 2022).

Bioethanol

Simple sugars found in pineapple peel and core can be used as food by yeast to create ethanol, a useful byproduct. The most widely used liquid biofuel worldwide is bioethanol (Mccance et al., 2021). The use of pineapple waste for bioethanol production has become an increasingly important strategy in recent years. One of the key benefits of producing ethanol from pineapple cannery by-products is the low cost of ethanol production, as well as the added advantage of solving the issue of pineapple waste disposal (Meena et al., 2022). Pineapple peel waste is rich in carbohydrates and reducing sugars, making it a viable substrate for

bioethanol production through fermentation and distillation. Due to its high carbohydrate content, pineapple peel is also used as biomass in bioethanol production, as these sugars can be fermented into ethanol (Fouda et al., 2022). The production of bioethanol from pineapple waste, particularly peels, has proven to be a cost-effective method. Pretreating pineapple peels with 0.1 M NaOH enhances the release of reducing sugars during microbial hydrolysis. Following 48 hours of fermentation, bioethanol yields of up to 5.9 g/L were achieved. Pineapple peel, which constitutes 29 to 40% of the total fruit weight and contains 36.3% cellulose, can be treated with water and heated at 100°C for 4 hours. After pretreatment, Saccharomyces cerevisiae yielded the highest ethanol production at 9.69 g/L after 72 hours of fermentation. Pineapple waste, with its high sucrose content, is considered an ideal feedstock for bioethanol production. Both Saccharomyces cerevisiae and Zymomonas mobilis have been shown to effectively ferment ethanol from pineapple waste. Enzymatic hydrolysis using cellulase and hemicellulase enzymes allows for about 8% ethanol production in 48 hours. In another study, Baker’s yeast (S. cerevisiae) immobilized in polyvinyl alcohol (PVA)-alginate beads successfully fermented liquid pineapple waste, with a theoretical ethanol production efficiency of 92.5% at a dilution rate of 0.05 h-1. The simple sugars derived from saccharification are efficiently fermented by these microorganisms (Meena et al., 2022). Carbohydrates in biomass are primarily represented by total structural carbohydrates, which make up about 37% of the dry weight of pineapple waste, making them the main component. The portion of pineapple peel that can be converted into ethanol is referred to as ethanol extractive, which constitutes 22.2% of the dry pineapple waste. In addition to ethanol extractive and structural carbohydrates, dry pineapple waste contains 7.5% acid-insoluble lignin, 0.96% acid-soluble lignin, 5.4% ash, 27.14% protein, and acetic acid. Studies have explored the production of bioethanol from pineapple peel using Saccharomyces cerevisiae as the fermenting yeast, focusing on fermentation pH. The maximum ethanol concentration achieved was 9.13% at a pH of 5.5. Another study found that after 30 hours of simultaneous saccharification and fermentation, the highest ethanol yield was 3.9% (v/v), representing 96% of the theoretical yield (Fouda et al., 2022). Additionally, the trend in the generation of bioethanol from pineapple fruit peels is correlated with the amount of reducing sugar seen during the fermentation period. The generation of ethanol rises as the reducing sugar falls. This occurs as a result of S. cerevisiae using fermentable carbohydrates to produce alcohol (Casabar et al., n.d.)**.**

Biogas

Pineapple peel is primarily composed of cellulose, hemicellulose, lignin, and pectin. Due to its high content of carbohydrates and proteins, along with its excellent biodegradability, it has shown strong potential as a raw material for biogas production (Rattanapoltee et al., 2014). Biogas, primarily composed of methane—a major greenhouse gas—can be generated from numerous feedstocks, especially food waste. The composition of biogas typically includes 50–75% methane, 19–34% carbon dioxide, and trace amounts of hydrogen. The presence of carbohydrates, proteins, lipids, high moisture content, and high biodegradability in waste materials makes them ideal candidates for biogas production. Additionally, food waste contains trace elements and organic substances that support microbial activity during the digestion process. Anaerobic digestion is the biological method used to produce biogas, involving the sequential actions of microbial communities through four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. While hydrogen has a higher energy density and burns cleanly to produce only water, it is typically produced biologically through anaerobic digestion using specific enzymes and microbes. Methods such as dark fermentation, photo fermentation, or combined fermentation are commonly used to generate hydrogen from organic substrates. Biogas with a methane concentration of 50–70% is suitable for use as a renewable energy

source for electricity generation or as cooking fuel. However, storage of hydrogen and methane poses challenges due to hydrogen's high reactivity and methane's low ignition threshold. To address this, a two-phase anaerobic digestion process is used to produce biohytane—a hybrid fuel containing both biomethane and biohydrogen (Nath et al., 2023).

Biodiesel

Biomass sources rich in triglycerides are commonly used as feedstock in biodiesel production. The resulting biodiesel primarily consists of fatty acid methyl esters (FAME), which are synthesized via the transesterification process. In this process, triglycerides react with alcohol in the presence of a catalyst, leading to the formation of FAME and glycerol. This involves the hydrolysis of the ester bonds between glycerol and fatty acids, followed by esterification. Pineapple waste has been explored as a carbon-rich substrate for biodiesel production due to its natural content of fermentable sugars such as glucose, fructose, and sucrose. When combined with sewage water and the yeast *Candida tropicalis* (MF510172), approximately 13 mL/L of lipids can be extracted from pineapple waste. These lipids are subsequently transesterified to yield biodiesel. Previous research also examined the use of pineapple peel and sugarcane bagasse as carbon sources to promote lipid production in microalgae, with pineapple producing a lower lipid yield (0.93 g/L) compared to sugarcane bagasse (1.24 g/L). More recent advancements have investigated the use of calcined pineapple leaves as a catalyst for biodiesel synthesis, demonstrating notable catalytic efficiency and requiring less activation energy for transesterification (Nath et al., 2023).

**Conclusion**

Pineapple waste, once considered a disposal challenge, is now recognized as a valuable resource rich in bioactive compounds with diverse industrial applications. The sustainable utilization of these by-products aligns with global efforts toward waste minimization, resource efficiency, and green innovation. Through effective recovery and processing methods, compounds such as bromelain, antioxidants, and dietary fibers can be extracted and applied across food, pharmaceutical, cosmetic, and biofuel industries. Moving forward, interdisciplinary collaboration, supportive policies, and advanced technologies will play a crucial role in optimizing these processes and ensuring commercial viability. Ultimately, turning pineapple waste into valuable products not only enhances sustainability but also supports a circular bioeconomy and rural livelihoods.

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Details of the AI usage are given below:

1.

2.

3.

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# CONFLICT OF INTEREST

The authors declare no conflict of interest.

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