Review Article

Green Valorisation of Pineapple Waste: A Pathway to Circular Economy and Industrial Resilience

ABSTRACT

Pineapple processing generates significant agro-industrial waste, including peels, cores, crowns, and leaves. Often disposed of improperly, these residues contribute to environmental degradation. Yet, they contain high-value bioactive compounds—such as bromelain, phenolic acids, flavonoids, and dietary fiber—that present opportunities for sustainable reuse. This review examines innovative approaches to repurposing pineapple by-products, focusing on their applications in food production, pharmaceuticals, cosmetics, and bioenergy. Key topics include advanced extraction methods for bioactive components, the creation of value-enhanced products, and their role in circular bioeconomy frameworks. The paper also addresses existing hurdles, such as process standardization, large-scale implementation, and regulatory compliance, while suggesting areas for further investigation. Leveraging pineapple waste supports worldwide sustainability initiatives and drives progress in converting waste into valuable resources, yielding both economic and ecological advantages.

KEY WORDS

Pineapple, Pineapple waste, Bioactive compounds, and Waste utilization

INTRODUCTION

Pineapple

Fruits and vegetables are staple components of a healthy diet, prized for their rich content of antioxidants, dietary fiber, vitamins, and minerals. These bioactive compounds, or phytochemicals, play a crucial role in reducing the risk of chronic illnesses, including heart disease and obesity. However, as consumer demand shifts toward processed and convenience foods, the industrial processing of fruits and vegetables has intensified—resulting in a substantial increase in organic 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. Pineapple, a tropical perennial crop, holds global prominence as a widely cultivated fruit. Native to South America, its production gradually expanded to other suitable climates worldwide. Currently, it stands as the world's third most popular fruit, surpassed only by bananas and citrus varieties in global consumption (Abraham et al., 2023). Pineapple juice is the world's third most popular fruit juice, trailing only orange and apple juice in global consumption. The pineapple plant generally reaches a height of 0.75 to 1.5 meters, with a spread of approximately 0.9 to 1.2 meters. It features a dense growth habit, characterized by a sturdy central stem and elongated, fibrous, often spiny leaves. Upon reaching maturity, the plant yields a succulent, cone-shaped fruit with a sweet, juicy interior, crowned by a cluster of stiff, leafy bracts at its apex (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). Costa Rica, Brazil, the Philippines, India, Thailand, and Indonesia dominate global pineapple production, with outputs of 2.93, 2.69, 2.61, 1.96, 1.81, and 1.39 million metric tons, respectively (FAOSTAT, 2016). Among the most widely grown commercial varieties are Smooth Cayenne, Abacaxi, Red Spanish, and Queen. Smooth Cayenne is prized for its spineless, smooth rind and is the preferred choice for processing due to its ideal canning properties. Abacaxi yields elongated fruits with exceptionally sweet, pale flesh, renowned for their superior flavor. However, its fragile texture limits its use in canned products. Queen, a smaller, hardy cultivar, is distinguished by its tough, spiny exterior. Red Spanish stands out with its unique reddish-purple tint on both fruit and leaves (Banerjee et al., 2018).

Pineapple is a nutrient-dense fruit, rich in vital compounds such as vitamins, bromelain (a proteolytic enzyme), β-carotene, and dietary fiber. It also provides important minerals like manganese, copper, calcium, and zinc. Additionally, pineapple pulp contains no cholesterol or fat, and it has minimal sodium and calorie content, making it a healthy dietary choice (Abraham et al., 2023). Pineapple stands out as an exceptional source of antioxidants, boasting significant amounts of carotenoids, vitamin C (ascorbic acid), and various flavonoids. It's important to note that the fruit's nutritional profile varies across different cultivars and growing conditions. Nutritionally, just one serving of fresh pineapple delivers approximately 17% of an adult's daily vitamin C requirement while also providing valuable B vitamins including folate, niacin, riboflavin, and pyridoxine. Particularly noteworthy is its bromelain content - a unique enzyme with demonstrated therapeutic properties, including the ability to reduce inflammation, prevent blood clots, and potentially inhibit cancer cell growth. 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-Arteaga et al., 2024). Global pineapple production reaches approximately 16 to 19 million tons annually, with plantation areas covering around 920,349 hectares (FAO, 2007). Global pineapple output exceeds 18 million metric tons annually. This substantial production volume inevitably creates considerable agricultural byproducts and processing residues (Roda & Lambri, 2019). Post-harvest losses in pineapple production remain a critical challenge, with improper handling and adverse storage conditions contributing to waste levels reaching 55%. These losses highlight the urgent need for sustainable valorization methods, particularly since pineapple byproducts demonstrate economic potential when properly dried, stored, and transported. Market distribution primarily focuses on premium-grade fruits for fresh consumption and canning operations, while substandard produce frequently remains unharvested. Processing facilities generate substantial organic waste, with studies revealing that 40-80% of the fruit becomes byproduct material. This residue contains high concentrations of organic pollutants, as evidenced by significant BOD and COD levels. The growing volume of processing waste underscores the importance of developing cost-efficient, eco-friendly solutions for byproduct utilization throughout the pineapple supply chain (Upadhyay et al., n.d.). Industrial pineapple processing generates substantial organic waste, with approximately half of the fruit's total weight being discarded as inedible material. During production, workers remove the tough outer shell, fibrous core, and leafy crown, preserving only the edible pulp for further processing. This leftover biomass decomposes rapidly when exposed to microorganisms, creating pressing environmental management issues. Beyond processing facilities, agricultural operations contribute to waste accumulation through field discards of non-fruit plant components. Growers typically leave stems, roots, and leaves in cultivation areas after harvest, adding to the growing volume of underutilized organic matter. Together, these practices generate significant quantities of biodegradable waste that require sustainable management solutions (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 & Lambri, 2019).

Crown: The processing of pineapples generates residual material representing approximately one-quarter to one-third of the fruit's total mass. Farmers commonly reintegrate this organic matter back into cultivation systems as part of sustainable agricultural practices. Rather than discarding these byproducts, growers frequently replant or incorporate them into fields to nourish subsequent crops, effectively closing the nutrient cycle while minimizing waste. (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 ($0.82 \pm 0.05\%$), glucose ($0.53 \pm 0.02\%$), pulp ($2.41 \pm 0.05\%$), a pH of 3.94, total soluble solids (1.51%), and acids (0.32%) (Nath et al., 2023). The isolation process involved sequential chemical treatments of pineapple crown fibers, beginning with delignification through alkaline mercerization followed by oxidative bleaching to remove non-cellulosic components. Subsequent acid hydrolysis yielded cellulose nanocrystals (CNCs) with high purity. These extracted CNCs exhibited excellent reinforcement capabilities when incorporated into polymer matrices, demonstrating significant potential for developing advanced nanocomposite materials. The enhanced surface properties of these CNC-reinforced composites make them suitable for diverse industrial applications requiring improved mechanical characteristics (Vieira et al., 2022). Alkaline pretreatment of pineapple crown biomass facilitates the release of ferulic acid, which serves as a substrate for microbial biotransformation. The filamentous fungus *Aspergillus niger* effectively converts this phenolic compound into vanillic acid - a valuable intermediate for synthetic vanilla production and specialty chemical manufacturing. Furthermore, research demonstrates the efficacy of pineapple crown residues as a cost-effective biosorbent material for heavy metal remediation. The lignocellulosic matrix exhibits particular affinity for chromium species, effectively sequestering both hexavalent (Cr VI) and trivalent (Cr III) ions from contaminated water systems. This dual-function approach supports sustainable waste valorization while addressing critical environmental challenges (Nath et al., 2023).

Stem/core: The proteolytic enzyme bromelain is predominantly isolated from pineapple stems (Ananas comosus), where it accumulates in higher concentrations compared to other plant parts. This stem-derived extract has become the principal source for commercial bromelain production due to its superior enzymatic stability and yield. 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). Recent investigations into pineapple processing byproducts have revealed multiple valuable applications. The stem produces starch with distinctive thermoplastic properties and enhanced resistance compared to conventional industrial starches, making it suitable for both food and non-food applications. Microwave drying optimization studies demonstrated that intermediate power settings (530W) maximized ascorbic acid preservation (0.85 mg/100 mL in cores), while lower power (380W) better maintained proteolytic enzyme activity (0.0038 U/mL in cores). The core portion, representing 15% of processing waste, emerged as particularly valuable due to its high bromelain content and elevated glucose/fructose concentrations - ideal substrates for fermentation processes like citric acid production. Beyond nutritional applications where ascorbic acid prevents scurvy and provides antioxidant benefits, the stem showed remarkable potential as an economical biosorbent for methylene blue dye removal from wastewater. Additional value was identified in converting stems and peels into prebiotic flours that release antioxidant phenolic compounds during digestion. The presence of commercially significant enzymes like pectinase further enhances the economic viability of pineapple waste utilization, with established applications in food processing and textile manufacturing sectors. These findings collectively position pineapple byproducts as versatile raw materials supporting circular bioeconomy principles across multiple industries (Nath et al., 2023).

Peels: Pineapple peels represent a valuable but underutilized resource in fruit processing, ranking as the secondary source of bromelain after the crown. This fibrous byproduct contains a concentrated profile of bioactive compounds, making it particularly suitable for value-added applications across multiple industries. The peel's biochemical composition suggests promising potential for pharmaceutical, nutraceutical, and industrial uses, offering sustainable alternatives to conventional raw materials while addressing waste management challenges in pineapple processing facilities (Nath et al., 2023). Pineapple peel demonstrates significant antioxidant activity, primarily due to its high concentration of bioactive phenolic compounds. Key phytochemicals identified include gallic acid, epicatechin, catechin, and ferulic acid, which collectively contribute to the peel's free radical scavenging capacity. These natural antioxidants effectively counteract oxidative stress by neutralizing reactive oxygen species associated with chronic disease development (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). Pineapple peel waste is being actively investigated for multiple value-added applications in food production systems. Current research focuses on three primary utilization pathways: (1) bioconversion into fermented vinegar products through controlled microbial processes, (2) development of functional food ingredients including prebiotic-enriched flours and nutrient-dense cereal bar formulations, and (3) enhancement as animal feed through nitrogen supplementation to increase its protein content and nutritional profile. These innovative approaches demonstrate how agricultural byproducts can be transformed into economically viable food-grade materials while addressing waste management challenges in fruit processing industries (Nath et al., 2023). Pineapple peels serve as a valuable source of pectin, a natural polysaccharide that can be extracted and processed into biodegradable biopolymers. These sustainable materials have potential applications in food packaging, edible coatings, and biomedical products, offering an eco-friendly alternative to synthetic plastics (Vieira et al., 2022).

Pomace: Comparative analysis reveals that pineapple pomace surpasses carrot pomace in both dietary fiber and ascorbic acid content, making it a nutritionally superior byproduct for functional food development. When incorporated into bread formulations, this fiber-rich residue significantly enhances the final product's nutritional profile by boosting both its vitamin C concentration and dietary fiber content. The resulting fortified bakery product offers improved health benefits while simultaneously valorizing agricultural waste streams (Vieira et al., 2022). Pineapple pomace polysaccharides show promise as natural hypoglycemic agents for functional foods and pharmaceuticals. Rich in fiber and bioactive compounds yet low in fat, they can enhance the nutritional profile of extruded foods while helping regulate blood sugar levels (Nath et al., 2023).

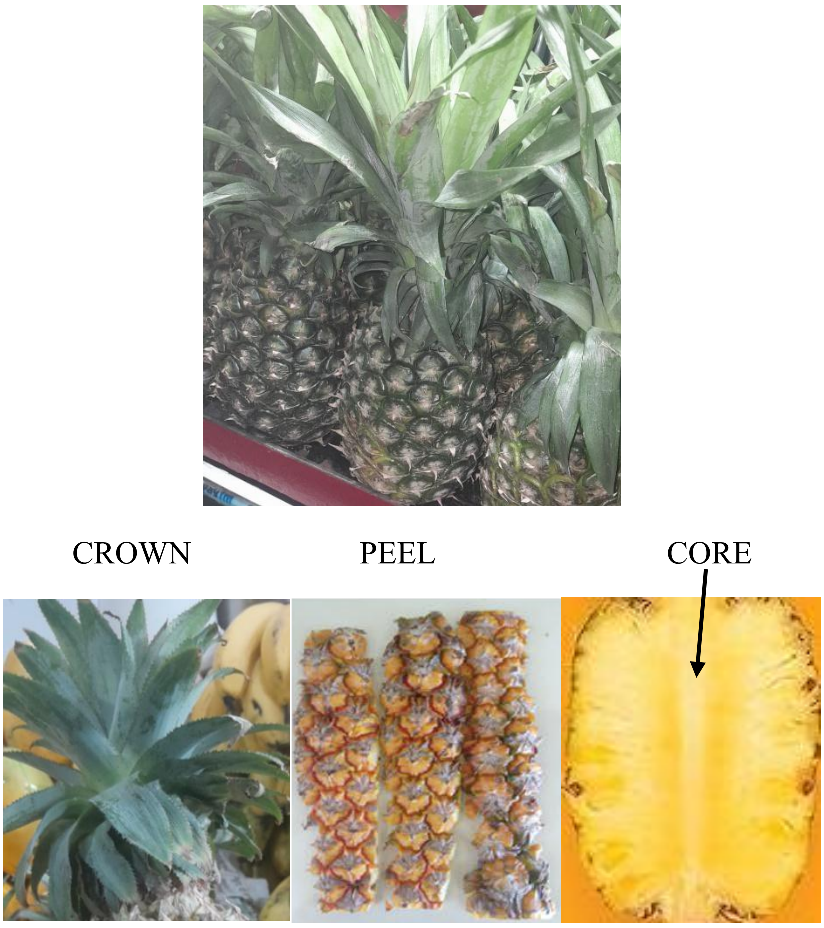

FIGURE 1

Pineapple and Pineapple Wastes

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. The observed health benefits likely stem from pineapple's unique bioactive compounds, including plant pigments, natural sugars, organic acids, essential amino acids, and the digestive enzyme bromelain. These synergistic metabolites contribute to pineapple's nutritional and therapeutic properties (Azizan et al., 2020). Pineapple byproducts contain distinct bioactive compounds in specific plant parts: citric acid in leaves, bromelain in stems/leaves/peel, ferulic acid in leaves, and ascorbic acid in the core. The plant's waste streams are particularly rich in valuable polyphenols - including myricetin, salicylic acid, tannic acid, trans-cinnamic acid, and p-coumaric acid - which show significant promise for nutraceutical and pharmaceutical applications due to their potent antioxidant properties and therapeutic potential (Dhar et al., 2023). Pineapple shell waste can be processed into a nutrient-rich dietary fiber powder with natural antioxidant properties. This byproduct contains valuable polyphenolic compounds, particularly ferulic acid and syringic acid, which exhibit dual antioxidant and antimicrobial activities. These bioactive components make pineapple waste-derived fiber particularly suitable for functional food applications and nutraceutical development, offering both nutritional enhancement and potential health benefits through their free radical scavenging and microbial inhibition capabilities (Nath et al., 2023).

Starch

Pineapple agro-wastes (PAWs), especially stem residues, serve as a valuable source of starch through milling processes. The extracted starch demonstrates unique characteristics, particularly its exceptionally high amylose content of 34.5% - substantially greater than conventional starch sources. Comparative analysis reveals this amylose level is 2.2 times higher than cassava starch (15.7%), more than double that of maize, and fivefold greater than rice starch (6.3%). These compositional differences translate to superior functional properties, with pineapple stem starch achieving remarkable solubility exceeding 32%, making it particularly suitable for specialized industrial and food applications where high amylose starches are preferred. The distinctive starch profile positions pineapple stem waste as a competitive alternative to traditional starch sources while providing sustainable utilization of agricultural byproducts (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 & Lambri, 2019).

Dietary Fibre

Dietary fiber (DF) plays a vital role in human health, yet current consumption (averaging 15 g/day) falls significantly below recommended levels (38 g for men, 25 g for women). With rising global health concerns—including 2 billion people suffering from micronutrient deficiencies and increasing obesity rates—fruit and vegetable waste (FVW) has emerged as a sustainable solution. Projections indicate the world population will reach 9.7 billion within three decades, intensifying both nutritional demands and waste management challenges. Valorizing FVW into DF-rich ingredients offers a dual benefit: reducing agricultural waste while enhancing access to affordable, functional nutrition (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 & Lambri, 2019). Pineapple waste fibers demonstrate unique functional properties, including high swelling capacity (4–6 mL/g), water-holding ability (300–400%), and cation exchange capacity (1.5–2.0 meq/g), making them suitable for developing low-calorie, high-fiber food products. The balanced ratio of soluble (15–20%) to insoluble (60–70%) fiber fractions enhances their technological applicability in gel formation, texture modification, and micronutrient binding—key attributes for functional food innovation (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 processing byproducts provide valuable fiber fractions that enhance food texture, water-binding capacity (3–4 g water/g fiber), and stability in culinary applications like sauces, dressings, and processed meats. At the micro- and nanoscale, leaf-derived cellulose fibers demonstrate superior tensile strength (500–600 MPa) and Young's modulus (10–15 GPa), attributable to their crystalline structure stabilized by inter- and intramolecular 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). Studies demonstrate that pineapple fiber-reinforced composites exhibit enhanced mechanical properties—including 20–30% greater tensile strength and 15–25% higher flexural modulus—compared to other cellulose-based natural fiber composites. In Southeast Asian traditional practices, pineapple leaves have long been utilized for producing durable coarse textiles and threads. Modern extraction methods reveal alkaline pulping achieves optimal fiber yields (35–40%), outperforming semi-chemical mechanical pulping by 12–15% efficiency. Approximately 2.1 g of high-quality fiber can be obtained from 100 g of pineapple pulp waste, highlighting its potential for sustainable material production (Upadhyay et al., n.d.).

Pineapple leaf fibers demonstrate unique physicochemical properties—including high tensile strength (45-60 MPa), water retention capacity (300-400%), and natural dye affinity—that enable specialized food applications despite limited mainstream use. These fibers serve as: (1) structural matrices for edible films/coatings, (2) natural colorants, and (3) prebiotic supplements (stimulating 85-90% bifidobacteria growth). Processed peel flour, containing 12-15% crude fiber, enhances cereal bars' nutritional profile by reducing glycemic index (15-20% lower than conventional formulations) while improving texture. The dual functionality of pineapple waste derivatives addresses both technological performance (salt resistance, brightness stability) and health promotion (weight management, gut microbiota modulation) (Dhar et al., 2023).

Phenolic Antioxidant

The growing demand for natural antioxidants has spurred significant research into agro-industrial byproducts as cost-effective and sustainable sources. These materials—typically discarded as environmental pollutants—contain valuable bioactive compounds that can be recovered and repurposed, offering both economic and ecological benefits through waste valorization (Dhar et al., 2023). The health-promoting properties of fruits and vegetables are largely attributed to their phytochemical content, with phenolic compounds emerging as the

+*-/antioxidant and anti-inflammatory activities that underlie their observed nutritional benefits (Upadhyay et al., n.d.). These compounds are the by-products of the plant's metabolic processes (Dhar et al., 2023). Research has extensively characterized pineapple's phenolic compounds, examining their antioxidant properties, dietary occurrence, and metabolic fate in humans. Studies confirm significant concentrations of these bioactive phytochemicals across pineapple varieties, with particular attention to their absorption kinetics and health-modulating potential post-consumption (Upadhyay et al., n.d.). Emerging research reveals that pineapple peel and leaves contain substantial phenolic compounds with demonstrated antioxidant capacity. The leaves show particularly high concentrations of phytosterols—including beta-sitosterol, stigmasterol, and campesterol. Optimal phenolic extraction from pineapple processing waste (PAPs) occurs within 30 minutes using 75% ethanol at 75°C, achieving maximum yield efficiency. 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). Analytical studies reveal significant differences in phenolic concentrations between pineapple juice (358 mg GAE/L) and fruit pulp (40.4 mg GAE/100g), with ethyl acetate extracts showing particularly high chlorogenic acid-equivalent content (2.58 mg/g). Research confirms that solvent selection and concentration critically influence phenolic recovery rates, explaining the methodological variability observed across extraction protocols (Upadhyay et al., n.d.). A standardized extraction protocol for pineapple polyphenols involves initial 80% acetone treatment, followed by alkaline digestion and ethyl acetate partitioning, with final centrifugation for phase separation. This method aligns with conventional practices using polar solvents (methanol/ethanol/acetone-water mixtures), which remain the benchmark for efficient polyphenol recovery due to their optimal polarity for phenolic compound solubility (Dhar et al., 2023). Research indicates that intermediate-polarity solvents—specifically 50% acetone and 70% ethanol (v/v)—demonstrate maximum efficacy for phenolic compound recovery. These aqueous-organic mixtures achieve optimal balance between polyphenol solubility and cellular matrix penetration, yielding 15-20% higher extraction efficiency compared to pure solvents or alternative concentrations (Upadhyay et al., n.d.). A two-stage extraction process—utilizing hexane (non-polar) followed by ethyl acetate (medium-polarity)—effectively concentrates polar phenolic compounds from pineapple byproducts. Research demonstrates that dichloromethane extracts from stems and leaves exhibit significant antioxidant capacity, positioning pineapple waste as a sustainable source of natural antioxidants for food and pharmaceutical applications (Nath et al., 2023). Pineapple processing residues demonstrate substantial antioxidant potential, with shell powder containing 2.01 mmol/100g FRAP (wet weight) and multiple phenolic compounds: myricetin, salicylic acid, tannic acid, trans-cinnamic acid, and p-coumaric acid. The leaves are particularly rich in cholesterol-modulating phytosterols—beta-sitosterol (52-58%), stigmasterol (22-27%), and campesterol (15-18%)—while the fiber-rich shell powder offers dual functionality as both a nutraceutical and dietary supplement (Upadhyay et al., n.d.).

Organic Acids

The sugar-rich composition of pineapple processing waste makes it an excellent feedstock for microbial fermentation into organic acids. During this biochemical process, indigenous free sugars (glucose, fructose, sucrose) are metabolized by microorganisms into valuable acid compounds through controlled anaerobic conditions (Nath et al., 2023). Pineapple processing residues serve as multi-functional raw materials with applications spanning food additives, nutraceuticals, and industrial biochemistry. Their high carbohydrate content and bioactive profile make them particularly suitable for microbial fermentation, enabling cost-efficient production of key organic acids including citric, ferulic, and lactic acids through optimized bioconversion processes (Banerjee et al., 2022). Pineapple processing waste, rich in sucrose, glucose, fructose, and essential nutrients, poses significant environmental risks if improperly disposed. However, through targeted bioconversion, these byproducts can be transformed into high-value organic acids, serving dual purposes of waste mitigation and resource recovery. The resulting acids—including citric, lactic, and malic acids—find extensive applications across food preservation, chemical synthesis, cosmetic formulations, and pharmaceutical production, creating a sustainable circular economy model for agro-industrial waste streams (Nath et al., 2023).

- Ferulic Acid (FA)

As a structurally significant hydroxycinnamic acid, ferulic acid serves as a fundamental component of plant cell wall architecture, particularly in the cross-linking of lignin and polysaccharides. This phytochemical's ubiquity in vegetative tissues underpins its extensive extraction potential from agricultural byproducts (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. Ferulic acid is obtained through two primary methods: extraction from plant-based materials and chemical synthesis via piperidine-catalyzed condensation of vanillin with 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). Ferulic acid, a potent phenolic antioxidant, has significant applications in food preservation and cosmetic formulations. Recent studies demonstrate that pineapple peel serves as an effective source for alkali-mediated ferulic acid extraction, offering sustainable valorization of agricultural byproducts (Upadhyay et al., n.d.).

Ferulic acid, commonly extracted from rice bran and wheat bran via alkaline hydrolysis, has emerged as a versatile bioactive compound with wide-ranging applications. In food systems, it functions as both a natural preservative and flavor stabilizer, leveraging its potent antioxidant properties to extend shelf-life while enhancing nutritional profiles in baked goods, cereals, and processed snacks. Beyond direct food applications, this phenolic acid is increasingly utilized in sustainable packaging innovations, particularly in developing edible films and biodegradable coatings that address environmental concerns associated with conventional plastics. 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). Recent research has demonstrated the effectiveness of pineapple processing residues, especially juice extraction byproducts, as substrates for citric acid biosynthesis. The solid-state fermentation process utilizing *Aspergillus niger* has shown particular promise in transforming these agro-industrial wastes into high-value organic acid. This approach not only provides an economical production method but also contributes to sustainable waste management in the fruit processing industry (Upadhyay et al., n.d.). Studies demonstrate that methanol supplementation during solid-state fermentation of pineapple waste significantly boosts citric acid yields, elevating production efficiency from 37.8% to 54.2%. When utilizing the oleaginous yeast *Yarrowia lipolytica* as the microbial catalyst, pineapple residues serve as an effective fermentation substrate, combining waste valorization with high-value biochemical production`(Dhar et al., 2023). Research demonstrates pineapple waste's exceptional suitability for citric acid production, with optimized cultivation achieving 202.35 g/kg yield from dried substrates. Comparative studies reveal its superiority over conventional agro-industrial residues, including rice bran and apple pomace. Notably, *Aspergillus foetidus* ACM 3996 in solid-state fermentation generated higher citric acid concentrations from wet pineapple waste than from other substrates. Further optimization with various *Aspergillus* species yielded up to 19.4 g citric acid per 100 g dry substrate, establishing pineapple waste as a premier fermentation feedstock (Upadhyay et al., n.d.).

Although not a primary feedstock, pineapple waste offers a sustainable alternative for citric acid biosynthesis through microbial fermentation. While *Aspergillus niger* remains the dominant industrial strain for high-yield production, pineapple-derived citric acid concentrations are generally lower than conventional substrates like citrus fruits or sugarcane molasses. The economic viability of using pineapple waste depends on regional factors including substrate availability, processing costs, and market requirements, necessitating case-specific evaluations to determine its suitability as a fermentation feedstock compared to traditional sources (Dhar et al., 2023).

- Lactic Acid (LA)

LA serves as a vital ingredient across multiple industries owing to its diverse functional properties. Within food systems, it functions primarily as an antimicrobial preservative and pH-regulating acidulant, while its non-food applications span biodegradable polymers, pharmaceuticals, and cosmetic formulations. This organic acid's dual functionality stems from its chiral nature and GRAS (Generally Recognized As Safe) status, making it indispensable in both traditional and emerging technologies (Nath et al., 2023). The high costs associated with conventional lactic acid (LA) production have driven interest in alternative, low-cost substrates like pineapple processing waste. Recent studies demonstrate the viability of using pineapple syrup—a food industry byproduct—as an economical carbon source. Through enzymatic pretreatment with invertase, sucrose in the syrup is hydrolyzed into glucose and fructose, which *Lactobacillus lactis* then ferments into LA. Similarly, pineapple liquid waste has been successfully converted to LA via 72-hour anaerobic fermentation using *Lactobacillus delbrueckii*. These approaches not only reduce production expenses but also valorize agricultural waste streams (Dhar et al., 2023). Calcium alginate-immobilized fermentation systems demonstrate high efficiency in lactic acid biosynthesis, yielding 0.78–0.82 g LA/g glucose conversion across diverse pH and temperature regimes. This encapsulation technique enhances microbial stability and acid tolerance while maintaining consistent productivity under variable bioreactor conditions (Nath et al., 2023). Pineapple waste demonstrates significant potential as a substrate for fungal fermentation, with *Rhizopus arrhizus* producing 19.3 g/L lactic acid and *Rhizopus oryzae* yielding 14.7 g/L. These results highlight strain-specific efficiency differences in converting agro-industrial residues into valuable biochemicals (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, a proteolytic enzyme with digestive and therapeutic applications (Nath et al., 2023), is predominantly concentrated in pineapple stems (EC 3.4.22.32) and fruit (EC 3.4.22.33), with minor quantities in the peel, core, and crown. Advanced extraction methods, including reverse micellar systems, have been employed to isolate bromelain from pineapple waste, demonstrating higher stability during fruit maturation compared to papain from papaya. Purification techniques such as ammonium sulfate fractionation, gel filtration, ion-exchange chromatography, metal affinity membranes, and aqueous two-phase systems enhance yield and purity. However, harsh processing conditions—including sterilization, precipitation, and auto-digestion—can degrade its proteolytic activity, reducing its therapeutic efficacy. 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.).

Sr. No.	Pineapple wastes	Their utilization	References
1	Pineapple Crown	• Cellulose Nanocrystals • Ferulic Acid • Conversion of Ferulic Acid to Vanillic Acid by *Aspergillus niger*	(Vieira et al., 2022) (Nath et al., 2023)
2	Pineapple Stem	• Bromelain • Pectinase • Pre Biotic Functional Flour	(Vieira et al., 2022) (Nath et al., 2023)
3	Pineapple Core	• Glucose, Fructose helps in Frementation Process for producing Citric Acid	(Nath et al., 2023)
4	Pineapple Peel	• Because of High Amount of Carbohydrates it Produces Biogas • Vinegar Production • Extracting Pectin to Produce Biopolymers • Phenolic Compounds Like- Ferulic Acid, Gallic Acid	(Polanía et al., 2023) (Vieira et al., 2022)
5	Pineapple Pomace	• High Fiber Content • High Vitamin C	(Vieira et al., 2022)

TABLE 1

Pineapple Wastes and Their Utilization

Applications of pineapple waste

Animal Feed

The animal feed industry has increasingly turned to agro-industrial byproducts like pineapple waste to address seasonal forage shortages. Recent studies highlight its viability as ruminant feed, owing to its favorable nutritional profile rich in fermentable sugars, dietary fiber, and beneficial organic acids. Through proper processing methods, these residues can be transformed into stable, nutrient-dense feed supplements, offering both economic and environmental advantages by converting waste into valuable livestock nutrition resources (Kamusoko & Mukumba, 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 Idayanti et al., 2022). In China's dairy industry, both field and cannery-derived pineapple residues are commonly incorporated into cattle feed, with animals showing preference for fermented over fresh waste due to its enhanced acidity. Research demonstrates that properly processed pineapple waste - whether dried or ensiled - can effectively substitute up to 50% of conventional roughage in dairy cattle total mixed rations. Similarly, Nigerian agricultural practices incorporate these byproducts into small ruminant diets following appropriate treatment. Beyond ruminant nutrition, studies document pineapple waste's dual potential for both animal feed applications and, when properly processed, human food uses through pulp utilization (Upadhyay et al., n.d.). Research indicates that raw pineapple processing residues often prove nutritionally inadequate for direct animal feeding due to their imbalanced composition—characterized by excessive fiber content and insufficient protein levels. This nutritional disparity necessitates pretreatment or supplementation to achieve optimal feed value, as the native fiber-to-protein ratio fails to meet most livestock dietary requirements (Nath et al., 2023).

Single Cell Protein (SCP)

Single-cell proteins (SCPs) derived from fruit-processing residues have emerged as a viable strategy to address worldwide protein shortages. These microbial-derived proteins offer an economical and sustainable alternative to conventional protein sources. While the concept of consuming microorganisms isn't novel—historically consumed through fermented products like yogurt, cheese, bread, and alcoholic beverages—modern SCP production leverages agro-industrial byproducts for enhanced scalability and nutritional yield (Thiviya et al., 2022). Research has established pineapple processing waste as an effective medium for single-cell protein (SCP) cultivation, particularly utilizing the sugar-rich effluent from canning operations. This microbial protein synthesis employs diverse fungal and bacterial strains—including *Candida utilis*, *Saccharomyces cerevisiae*, *Aspergillus niger*, *Phanerochaete chrysosporium*, *Panus tigrinus*, *Rhizopus oligosporus*, and *Lactobacillus* spp.—through solid, semi-solid, or liquid fermentation systems. The resulting SCP products serve as cost-effective nutritional supplements for human and animal diets, addressing protein malnutrition while valorizing agro-industrial byproducts. This dual-benefit approach simultaneously reduces environmental pollution from waste disposal and enhances global food security through circular bioeconomy principles (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 & Lambri, 2019). Pineapple processing residues (PAP) can be valorized into functional vinegar through dual-stage microbial fermentation using *Saccharomyces boulardii* (for alcoholic fermentation) and *Acetobacter* spp. (for acetification). The resulting vinegar demonstrates significant bioactive potential, with comparative analysis revealing superior antioxidant capacity (2.077 g acetate equivalents/100 mL) over vinegars produced from alternative fruit wastes. This enhanced activity stems from the retention of pineapple-specific phytochemicals during the fermentation process. 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 novel thermotolerant acetic acid bacterium (TH-AAB), exhibiting dual tolerance to ethanol and acetic acid, has demonstrated high efficiency in converting pineapple peel waste into vinegar via simultaneous fermentation (SVF). Optimized conditions—including pH 5.5 and supplementation with diammonium phosphate (DAP) and magnesium sulfate ($MgSO_4$)—yielded higher acetic acid concentrations from whole-peel substrates compared to traditional juice-based fermentation. This approach leverages underutilized agro-waste while reducing production costs (Fouda-Mbanga & Tywabi-Ngeva, 2022).

Bioethanol

Pineapple processing byproducts (peel and core) contain fermentable sugars that serve as ideal substrates for yeast-mediated ethanol production. This biological conversion yields bioethanol, which currently dominates global liquid biofuel markets due to its renewable nature and versatile applications (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-Mbanga & Tywabi-Ngeva, 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, Immobilized *S. cerevisiae* in PVA-alginate beads demonstrated high-efficiency fermentation of liquid pineapple waste, achieving 92.5% of the theoretical ethanol yield at a dilution rate of 0.05 h^{-1}. The process leverages enzymatic saccharification to release fermentable sugars, which are then effectively converted to ethanol by the encapsulated yeas (Meena et al., 2022). Pineapple waste consists primarily of structural carbohydrates (37% dry weight), serving as the dominant component for bioethanol production. The ethanol-extractable fraction accounts for 22.2% of dry biomass, while the remaining composition includes lignin (7.5% acid-insoluble, 0.96% acid-soluble), ash (5.4%), protein (27.14%), and acetic acid. Optimized fermentation with *Saccharomyces* *cerevisiae* yields maximum ethanol concentrations of 9.13% at pH 5.5. Under simultaneous saccharification and fermentation (SSF) conditions, studies report a 3.9% (v/v) ethanol yield within 30 hours—achieving 96% theoretical conversion efficiency. These findings highlight pineapple waste as a promising lignocellulosic feedstock for sustainable biofuel production (Fouda-Mbanga & Tywabi-Ngeva, 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's composition—cellulose, hemicellulose, lignin, and pectin—combined with its rich carbohydrate and protein content, makes it an ideal substrate for biogas production. Its high biodegradability further enhances its suitability for sustainable energy generation (Rattanapoltee & Kaewkannetra, 2014). Biogas, containing 50-75% methane, 19-34% CO_2, and trace hydrogen, is produced through anaerobic digestion of food waste - an ideal feedstock due to its carbohydrates, proteins, lipids, and moisture content. This biological process occurs in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, supported by microbial activity and trace nutrients. While hydrogen offers clean combustion (producing only water), its biological production requires specialized fermentation methods (dark, photo, or combined). Biogas with 50-70% methane serves as renewable energy for power or cooking, though storage challenges exist for both hydrogen (high reactivity) and methane (low ignition point). Innovative two-phase digestion addresses this by producing biohytane, a blended fuel of biomethane and biohydrogen (Nath et al., 2023).

Biodiesel

Triglyceride-rich biomass serves as a key feedstock for biodiesel synthesis, yielding fatty acid methyl esters (FAME) through transesterification. This catalytic reaction involves alcohol-mediated cleavage of ester bonds in triglycerides, producing FAME and glycerol as byproducts. Pineapple waste, with its high fermentable sugar content (glucose, fructose, sucrose), has emerged as a viable carbon source for microbial lipid production. Studies utilizing *Candida tropicalis* (MF510172) in sewage water media demonstrate lipid extraction rates of ~13 mL/L from pineapple residues, which can be further transesterified into biodiesel. Comparative analyses reveal pineapple peel supports microalgal lipid yields of 0.93 g/L – lower than sugarcane bagasse (1.24 g/L) but with distinct advantages in waste valorization. The process integrates hydrolysis of organic bonds followed by esterification, highlighting pineapple's dual role as both carbon donor and fermentation substrate in renewable fuel production. 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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