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From Waste To Vitality: Pineapple Peel In Detox Drink – A Review

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Abstract: Rising concerns about agro-industrial waste have led to a growing focus on sustainable solutions, with pineapple peel – an abundant by-product of pineapple processing – emerging as a resource of interest. This review highlights its nutritional value and bioactive composition, emphasizing its potential role in formulating health-focused detox drinks. Pineapple peel contains significant amounts of dietary fiber, phenolic compounds, flavonoids, bromelain, and essential micronutrients, offering antioxidant, anti-inflammatory, antimicrobial, and possible detoxifying effects. The paper compiles existing research on its composition, health benefits, and extraction techniques, and assesses its applicability in food and beverage products. It also explores the environmental and economic benefits of utilizing pineapple peel, supporting waste reduction and sustainable development. By aligning with circular economy principles, the review promotes a shift from waste disposal to value creation – paving the way for innovation in functional beverages that meet both health and sustainability goals.

Keywords: Sustainable Development, Waste Management, Pineapple Peel, Bioactive Compounds, Bromelain, Antioxidant Activity, Detoxification

Introduction

The escalating generation of waste emanating from food industrial and agricultural activities presents a significant global challenge in the present era [1-3]. These sectors, crucial for sustaining human populations, inherently produce substantial quantities of by-products and discards throughout their operations, from primary production to processing and consumption [1, 4]. The sheer volume of this waste stream poses considerable environmental, economic, and social burdens, necessitating urgent attention and innovative strategies for its sustainable management and valorization [1-2,4]. Globally, the magnitude of food industrial and agricultural waste production is staggering. Fruit and vegetable processing industries, in particular, are recognized as major contributors to the overall food waste stream. With evolving dietary patterns and a growing global population, the demand for processed fruits and vegetables has amplified considerably, consequently leading to an increase in the generation of associated wastes [1]. While precise global figures fluctuate depending on the source and methodology of estimation, it is clear that we are dealing with hundreds of millions, if not billions, of tonnes of waste annually. For instance, one source indicates that fruit and vegetable industries generate substantial by-products, largely consisting of peels, pulp, and seeds to a lesser degree, potentially representing 25 to 60% of the fruit's weight [2]. In the specific context of pineapple, global production was estimated at an impressive 25.4 million metric tons in 2019. Concomitant with this massive production, substantial waste is generated during pineapple processing, primarily in the form of peels, cores, and crowns, which can account for a significant 45–65% of the total fruit weight [5]. Malaysia, a notable pineapple producer, is reported to generate approximately 83,000 tonnes of pineapple peel waste (PPW) annually [4,6]. India, another major player in fruit and vegetable production, cultivates pineapple across a substantial area, yielding a significant output, estimated at 1.7 million tonnes annually. This robust production in India also translates into a considerable quantity of pineapple processing waste, estimated to be around 30-40% of the fruit weight, encompassing crown, peel, stem, core, and pomace [7]. Indonesia is also recognized as among the biggest in the world pineapple producers, with a yearly output reaching around 1.396 million tonnes [4, 8]. These figures underscore the widespread generation of pineapple waste across various regions.

The accumulation of food industrial and agricultural waste, if not managed effectively, precipitates a cascade of adverse environmental and other detrimental effects [2-3, 9]. A significant portion of this waste ends up in landfills, where its decomposition contributes to the emission of greenhouse gases, notably methane, a potent contributor to climate change [3, 4]. Furthermore, the sheer volume of waste necessitates extensive landfill space, posing challenges for land use and potentially leading to soil and water contamination through leachate [8-9]. The uncontrolled dumping of agricultural waste can also disrupt local ecosystems and create breeding grounds for pests and vectors of disease [9]. Beyond environmental impacts, there are economic costs associated with waste disposal, including transportation, landfill fees, and potential loss of valuable resources contained within the waste [2]. Socially, the mismanagement of waste can lead to unpleasant odours, aesthetic degradation of landscapes, and potential health hazards for communities living near disposal sites [8]. Recognizing these multifaceted negative consequences is crucial for driving the adoption of sustainable waste management strategies.

The pineapple is a widely cultivated and commercially significant tropical fruit, prized for its flavour and nutritional content [10-12]. During its processing for various products such as canned fruits, juice, concentrates, and jams, substantial quantities of non-edible parts are generated, collectively referred to as pineapple waste [3, 5, 10]. Among these, pineapple peel waste (PPW) constitutes a major fraction, accounting for a significant percentage of the total pineapple waste [6-7, 13]. Often discarded as waste, PPW presents both a disposal challenge and a significant opportunity due to its rich composition [6, 13-14]. Chemical analysis reveals that pineapple peel is a complex matrix containing a variety of valuable components, including carbohydrates, dietary fibre, protein, lipids, ash, and a wealth of bioactive compounds such as phenolic compounds, vitamins (like vitamin C), enzymes (notably bromelain), and organic acids [2-3, 15]. The specific composition can vary depending on the pineapple variety, ripeness stage, and processing methods [3-4]. The presence of these constituents underscores the potential of PPW as a valuable resource rather than a mere waste product [14-16].

In recent years, there has been a notable surge in consumer interest and demand for products perceived to offer health and wellness benefits, including detox drinks. These beverages are often marketed for their purported ability to eliminate toxins from the body, boost energy levels, aid digestion, and support weight management. This rising demand is fueled by increasing health consciousness, a desire for natural and plant-based remedies, and the influence of health and wellness trends. While the scientific evidence supporting the detoxification claims of many commercially available drinks varies, the underlying consumer interest in beverages that promote well-being remains strong [17]. This trend presents an opportunity to explore natural and sustainable ingredients for formulating such drinks, potentially aligning with both consumer preferences and environmental sustainability goals.

Given its rich reservoir of bioactive compounds, *pineapple peel emerges as a particularly promising and sustainable ingredient for the formulation of detox drinks* [13, 15, 18]. The presence of phenolic compounds, known for their potent antioxidant properties, can contribute to the overall health benefits associated with detox formulations by combating oxidative stress [3, 6, 18]. Furthermore, the dietary fiber content in pineapple peel can support digestive health, a key aspect often highlighted in the context of detoxification [2, 15]. The vitamins and other micronutrients present can also contribute to the nutritional profile of a detox drink [4, 13]. Utilizing pineapple peel not only adds potential health benefits to a beverage but also addresses the environmental concern of pineapple waste disposal by transforming a by-product into a valuable ingredient [15-16]. This approach aligns with the principles of a circular economy, where waste streams are repurposed and valorized [3, 13].

This review explores the untapped potential of pineapple peel as a sustainable and health-promoting ingredient for detox drinks. Often discarded as waste, pineapple peel is rich in valuable nutrients and bioactive compounds that could significantly contribute to the growing demand for natural, functional beverages. The goal of this paper is to bring together existing research on the nutritional makeup and health benefits of pineapple peel, with a focus on compounds like phenolic acids, flavonoids, and antioxidants known for their detoxifying and protective effects.

The review also takes a closer look at the biological activities linked to these compounds, supported by findings from both lab-based and animal studies. In addition, it examines various methods used to extract and process these beneficial components, evaluating how efficient, sustainable, and suitable they are for use in food and beverage products. Finally, the paper discusses how pineapple peel – either as an extract or in processed form – can be integrated into detox drink formulations, considering key factors like functionality, shelf life, and consumer acceptance. By bringing together insights from across the literature, this review aims to lay the groundwork for future innovation, encouraging the use of pineapple peel as a valuable, eco-friendly ingredient in next-generation detox beverages.

Pineapple Waste

A highly important tropical fruit, pineapples (Ananas comosus) are grown in many tropical nations across the world, including the Philippines, Thailand, Indonesia, Malaysia, Kenya, India, China, and South America [3, 20]. This economically important crop, belonging to the family *Bromeliaceae*, is enjoyed for its appealing sweet flavour and is consumed in its natural form or processed into a wide array of products such as juices, concentrates, jams, jellies, purees, and canned fruits [6, 10, 20-23]. The increasing demand for pineapple consumption globally has unfortunately led to the generation of enormous amounts of solid waste as a direct consequence of pineapple fruit processing and harvesting practices [3, 6]. The pineapple processing industry, involved in the production of canned pineapple and juice, is a major contributor to the accumulation of solid waste [21]. It has been estimated that a significant portion of the total weight of the pineapple, ranging from 45% to 65%, ends up as waste [5]. According to some estimates, the core, outer peel, and crown of the fruit, together with about 80% of its total weight, is thrown away [3, 20]. Globally, this translates to a staggering amount of pineapple waste, with estimations reaching approximately *22.5 million tons annually* [20]. According to estimates from the Food and Agriculture Organization (FAO) of the United Nations, between 50 and 65 percent of the fruit's weight is made up of pineapple waste [16]. The sheer volume of this waste highlights the urgent need for effective management and valorisation strategies [26].

This substantial quantity of pineapple waste comprises various components, including *peel, core, crown, leaves, stem, and pomace (leftover pulp)* [1-4, 7, 16]. The current manufacturing sector treats pineapple core and peel and leaves as industrial waste material. The processing waste contains 40-50% (w/w) weight ratios of peels and kernel (core) together with pomace. The pineapple juice canning industry generates major waste output by processing 60% of all produced pineapple waste which results in disposal of approximately half of the total processed pineapple mass [16]. This growing figure of articles, authors, institutions and journals provides an insight into the increasing importance of addressing agricultural wastes. Identifying the key authors and institutions involved in this field can facilitate the recognition of references and potential collaborators for advancing research and implementation processes [27].

In India, pineapple is also abundantly available, with a cultivation area of approximately 102,960 hectares and an annual production of around 1.7 million tonnes. Being the seventh-largest producer globally, India also faces the challenge of managing the waste generated from its pineapple industry. Pineapple processing in India uses the standard waste forms of crown and peel and stem and core and pomace which together constitute approximately fifty percent of the total fruit weight. Rough calculations indicate that for every acre producing approximately 12-18 tonnes of pineapple, around 76-92 tonnes (14.4-19.2 tonnes on a dry basis) of on-farm waste like leaves and stems, and an additional 9 tonnes (1.35 tonnes on a dry basis) of processing waste such as peels, crowns, and cores are generated [7]. The efficient processing and value addition of fruits like pineapple are seen as crucial for significantly boosting farmers' income and promoting

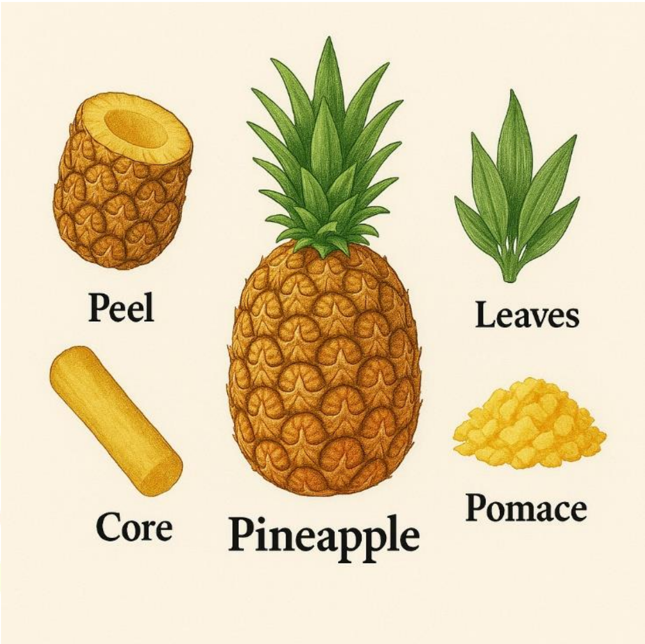

Figure 1

Pineapple and Its Processing Wastes: A visual representation showing key by-products of pineapple processing – Peel, Core, Leaves, and Pomace

indigenous processing industries. However, the north-eastern region of India, despite its potential, currently utilises only 12% of its agro-produce for food processing, highlighting the need for coordinated efforts and infrastructure development [22].

Pineapple Peel

Among the different components of pineapple waste, pineapple peel constitutes a significant portion, estimated to be about 30-40% of the total pineapple waste [1, 6, 12]. Given the vast amounts of pineapples processed globally, the quantity of pineapple peel waste generated is substantial. In Malaysia alone, approximately 83,000 tons of pineapple peel waste (PPW) are estimated to be produced annually [6]. While specific worldwide data solely for pineapple peel waste was not explicitly stated in all sources, considering it forms a substantial percentage of the total waste (estimated at 22.5 million tons annually), the global generation of pineapple peel waste would amount to millions of tons. Similarly, in India, with an estimated total pineapple waste of around half the production (1.7 million tonnes), the pineapple peel waste would also be in the order of hundreds of thousands of tonnes annually.

Studies demonstrate that the nutritional elements present in pineapple peel align with components found in pineapple flesh while including antioxidants as well as sugar and water and vitamins and flavonoids together with carotenoids and minerals [6, 16]. The antioxidant properties of Pineapple peel are vital to health industries and cosmetic manufacturing together with chemical applications [3, 6, 11, 16, 25]. Chemical analysis confirms pineapple peels contain high levels of available carbohydrates at 42.29% combined with dietary fiber that accounts for 30.20% of their content. Other reports confirm that pineapple peel contains approximately 55.52% carbohydrates and 4.39% ash alongside 14.80% crude fiber [20]. Pineapple peel also contains lignocellulose, which is composed of lignin, cellulose, and hemicellulose [3, 8]. Lignocellulose analysis of pretreated pineapple peel waste has shown hemicellulose content up to 22.1% and cellulose content up to 55.2%, with a low lignin content of 0.41% in some cases [8]. Phytochemical screening of pineapple peel extracts has also revealed the presence of secondary metabolites of therapeutic relevance, including alkaloids, phenols, and tannins [9]. The peel is also a potential source of essential oils composed of esters, alcohols, aldehydes, and ketones [16]. Moreover, pineapple peel contains a significant amount of phenolic compounds [2-3, 5, 10, 14, 23], including specific compounds like gallic acid, catechin, epicatechin, and ferulic acid [2-3]. Notably, pineapple peel is also a source of *bromelain*, a proteolytic enzyme with high integrated value [3, 12]. Proximate analysis has further shown that dry pineapple peels contain *protein, fat, and ash* [4, 9]. The pineapple peel contains more fat than eleven cereal products based on analysis results [9]. The antioxidant activity of compounds extracted from pineapple peel is critical and often determined using multiple methods like DPPH radical scavenging assay, ABTS, and CUPRAC [18].

The prevalent practice of discarding pineapple waste, particularly the peel, after consuming the edible parts, significantly contributes to environmental pollution [3, 6, 9]. Dumping these wastes in landfills leads to several problems, their high-water content accelerates the rotting process, causing severe environmental pollution, including air contamination from rotten odours and microbiological growth leading to further contamination [3, 6].

Furthermore, the limited availability and high cost of landfill space, coupled with transportation expenses, often result in unattended waste [6, 25]. Recognizing these environmental and economic challenges, there is a growing focus on converting pineapple waste, including the peel, into valuable products through various methods such as extraction, fermentation, and thermal pretreatment, aiming for a waste-to-wealth approach and a more sustainable management of these abundant agricultural residues [3-4, 6-9, 14-15, 25].

Nutritional And Bioactive Composition Of Pineapple Peel

Pineapple peel, a significant by-product of pineapple processing, has garnered considerable attention as a reservoir of valuable nutritional and bioactive compounds [1, 3, 6, 15]. Its composition positions it as a potential resource for various industrial applications, contributing to sustainability and the creation of value-added products [1, 3-4, 6, 15, 26].

Pineapple peel exhibits a diverse nutritional profile, varying slightly depending on the pineapple variety, growing conditions, and analytical methods employed [1, 3, 6, 9, 15, 21]. Key nutritional components include:

Moisture Content: The moisture content of fresh pineapple peel is notably high, contributing to its rapid spoilage. However, dried pineapple peel has a significantly lower moisture content, typically ranging from 5.10% to 6.60% [9, 15]. This reduction is achieved through drying processes such as oven drying, freeze-drying, or air drying [6, 9, 15, 21].

Protein: Pineapple peel contains a modest amount of protein, with reported values ranging from 3.23% to 9.13% on a dry weight basis [15, 17]. Some studies have even indicated protein content around 5.78% [9].

Lipids (Fats): The lipid content in pineapple peel is generally low, ranging from 0.54% to 5.57% of the dry weight [9, 15].

Ash (Minerals): The ash content, indicative of the mineral content, typically falls within the range of 1.11% to 4.81% of the dry peel [9, 15, 17,21]. Minerals such as calcium, potassium, phosphorus, iron, manganese, and zinc have been identified in pineapple peel [14, 15].

Carbohydrates: A significant portion of pineapple peel is composed of carbohydrates, ranging from 15.92% to 75.68% of the dry weight [9, 15, 21]. These include both insoluble and soluble sugars [6, 21].

Dietary Fibre: Pineapple peel is a rich source of dietary fiber, with total dietary fibre (TDF) content reported as high as 69.64% to 70.6% of the dry weight [1, 15, 23]. A significant portion of this is insoluble dietary fibre (IDF), which can constitute over 67% of the dry weight. Soluble dietary fibre (SDF) is present in smaller quantities [1, 15].

Vitamins: Pineapple peel contains various vitamins, including vitamin C [9, 11, 17, 25], vitamin A, and B-complex vitamins [14, 25].

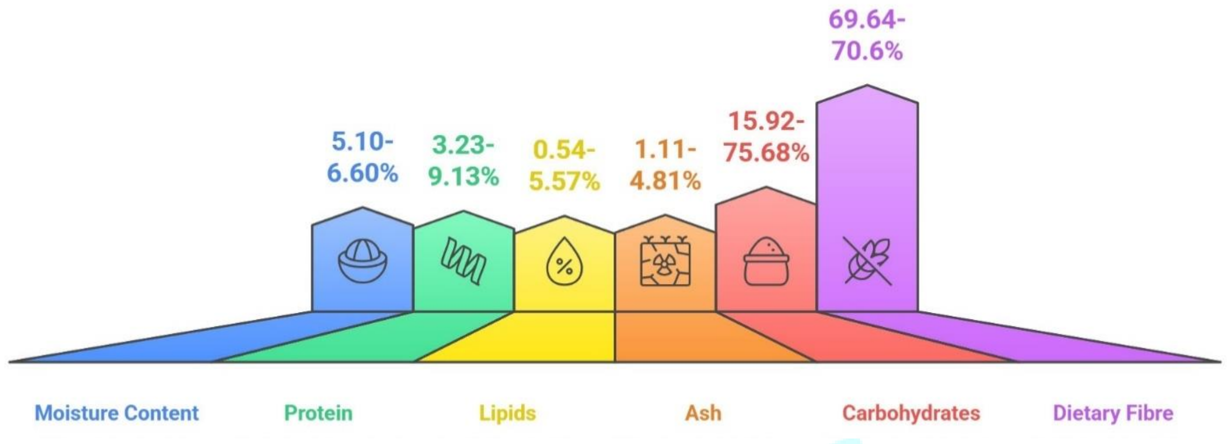

Figure 2

Nutritional Composition of Pineapple Peel: The chart highlights the key nutritional components found in pineapple peel, including moisture, protein, lipids, ash, carbohydrates, and dietary fiber.

Antioxidant Activity of Pineapple Peel

Pineapple peel exhibits notable antioxidant activity due to the presence of various bioactive compounds, primarily phenolic compounds and flavonoids [1-3, 5-6, 11-15, 20, 23-25]. These compounds are secondary metabolites known for their ability to scavenge free radicals and protect against oxidative damage [1-3, 5-6, 11-13, 15, 20, 23, 25-26, 30].

Phenolic Compounds: Pineapple peel is a source of diverse phenolic acids, including gallic acid, ferulic acid, chlorogenic acid, epicatechin, catechin, p-coumaric acid, and vanillic acid [2, 5, 11-12, 15]. Total phenolic content (TPC) in pineapple peel extracts has been reported in a wide range, from 2.82 mg GAE/g to 5803.21 mg GAE/g of dry extract, depending on the extraction solvent and method [15, 23]. Green extraction technologies like ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) can enhance the recovery of these phenolic compounds [2, 5, 23]. Fermentation processes can also significantly increase the release of bound phenolic compounds, further boosting antioxidant activity [5, 20].

Flavonoids: Flavonoids, another class of polyphenolic compounds, are also present in pineapple peel [6, 9, 11, 23, 30-32]. Total flavonoid content (TFC) has been reported as 1.56 mg QE/g to 9067.09 mg QE/g of dry extract [15, 23].

Antioxidant Activity Assays: Research on the antioxidant properties of pineapple peel extracts utilized multiple in vitro screening methods which included DPPH radical scavenging assay, ABTS assay and FRAP assay [2, 5-6, 11, 13, 15, 18, 20, 23]. Peel extracts have demonstrated significant DPPH radical scavenging activity, with inhibition percentages ranging from 27% to over 93%. Similarly, ABTS + radical scavenging activity has been observed, indicating the peel's capacity to donate electrons and neutralise radicals [5, 18, 23]. The antioxidant activity often correlates with the total phenolic and flavonoid content, although the specific compounds present and their synergistic effects also play a role [11, 18, 20].

Enzyme: Bromelain

The proteolytic enzyme mixture known as bromelain finds its main distribution in pineapple peel along with stem and core components [1-2, 6-7, 12, 25].

Activity Levels: While the highest bromelain concentration is often found in the stem and crown [2, 7], pineapple peel also contains considerable amounts of this enzyme [6, 12]. Studies have shown varying levels of bromelain activity in peel extracts, with some reporting comparable or even higher activity than other pineapple parts depending on the variety and extraction method [7, 12].

Extraction and Purification: The extraction procedure along with purification of Bromelain emerges from pineapple peel through solvent extraction or microwave and ultrasound technology [2, 6, 7]. Purification steps often involve ammonium sulphate precipitation, dialysis, and chromatography to increase the enzyme's purity and specific activity [12, 22]. Novel purification methods, such as reverse micellar extraction and aqueous two-phase systems, have also been explored to enhance yield and reduce costs [22].

Stability: The stability of purified bromelain is crucial for its applications. Studies have shown that bromelain activity can be affected by factors such as pH, temperature, metal ions, and the presence of certain chemical additives. Optimal stability is generally observed at lower temperatures and within a specific pH range (4.0-5.0). Certain compounds, such as calcium ions, EDTA, and some sugars and organic acids, can enhance bromelain activity [12].

The industrial applications of bromelain from pineapple peel extend throughout the food production sector and pharmaceutical field because of its proteolytic properties and antioxidant qualities [2, 12, 22, 25]. Its potential in developing antimicrobial agents and therapeutic treatments is also being explored [2, 18, 25].

All in all pineapple peel is a valuable by-product rich in nutritional components, potent antioxidants, and the enzyme bromelain. Its comprehensive bioactive composition positions it as a promising source for various applications across the food, pharmaceutical, cosmetic, and chemical industries, contributing to waste valorisation and sustainable resource utilization [1, 3-4, 6, 15, 26].

Potential Health Benefits and Detoxifying Effects of Pineapple Peel

It's fascinating to discover the hidden treasures within what we often discard, and pineapple peel is a perfect example of such a resource, brimming with potential health benefits and even some detoxifying effects. While the sweet, juicy flesh of the pineapple is widely enjoyed, its often-overlooked peel is a powerhouse of valuable compounds that could significantly contribute to our well-being [2-3, 15, 23].

One of the most remarkable aspects of pineapple peel is its impressive antioxidant activity [1-2, 5, 6, 9, 11, 15, 23]. This is largely attributed to the rich array of phenolic compounds and flavonoids it contains [1-3, 5-6, 10-11, 15, 20]. These natural plant metabolites are known for their ability to scavenge harmful free radicals in the body, which are implicated in ageing and various chronic diseases [6, 10]. These compounds are known to control cellular functions and combat free radicals, potentially lowering the risk of chronic conditions like obesity, diabetes, and cardiovascular diseases [1].

Beyond its antioxidant prowess, pineapple peel exhibits significant anti-inflammatory effects [1-3, 5-6, 9, 11, 15, 25]. This can be largely credited to bromelain, a well-studied proteolytic enzyme abundant in pineapple, including the peel [1-3, 6, 9, 25]. Bromelain has been shown to help reduce post-surgery or injury swelling and functions as an anti-inflammatory agent throughout body, potentially easing symptoms of conditions like arthritis and joint pain [6, 25]. Research suggests that bromelain achieves this by inhibiting the expression of pro-inflammatory markers [12]. Other phenolic compounds present in the peel may also contribute to these anti-inflammatory actions [5, 20].

While the term 'detoxifying' can sometimes be misleading, pineapple peel does possess properties that can support the body's natural detoxification processes [2, 6, 25, 28, 33]. Studies have indicated that pineapple waste, including the peel, can act as a biosorbent for removing heavy metals like mercury, lead, cadmium, copper, nickel, and zinc from the environment [6, 25, 33]. The presence of organic acids such as citric acid in pineapple peel [1, 25] may also play a role in this process [28]. Furthermore, consuming fruits and vegetables, including pineapple and its peel, can support liver and kidney function, key organs involved in detoxification, by providing essential nutrients and promoting overall health [28-29, 34]. The high water and fiber content of pineapple peel [1-3, 6, 9, 15, 20, 23, 34], can further aid in the elimination of waste products from the body [34].

The potential health benefits of pineapple peel extend even further:

Antimicrobial Properties: Extracts from pineapple peel have demonstrated inhibitory effects against various bacteria, including foodborne pathogens like *Escherichia coli* and *Staphylococcus aureus* [6, 11, 15, 18]. This suggests a potential role in food preservation and combating infections [6, 25].

Anticancer Potential: Preliminary research hints at the possibility of compounds in pineapple peel, such as bromelain and certain antioxidants, having anticancer properties by combating tumours and preventing cancer cell growth [2, 6, 9, 25].

Digestive Aid: The peel carries additional benefits because it helps digestion and might lower parasite counts and eliminate constipation and reduce Irritable Bowel Syndrome (IBS) symptoms [9, 25]. The microorganisms in your gut flora can benefit from the use of this substance to stay in good health [9].

Dental and Bone Health: Pineapple peel contains manganese and vitamin C, which are beneficial for maintaining healthy gums and tissues, as well as contributing to the development, strengthening, and repair of bones and teeth [9, 25].

Vision Protection: The presence of beta-carotene and vitamin C in the entire pineapple plant, including the peel, may help fight degenerative eye disorders like glaucoma [9, 25].

Blood Clot Reduction: Bromelain in pineapple can help prevent the formation of blood clots [9, 25].

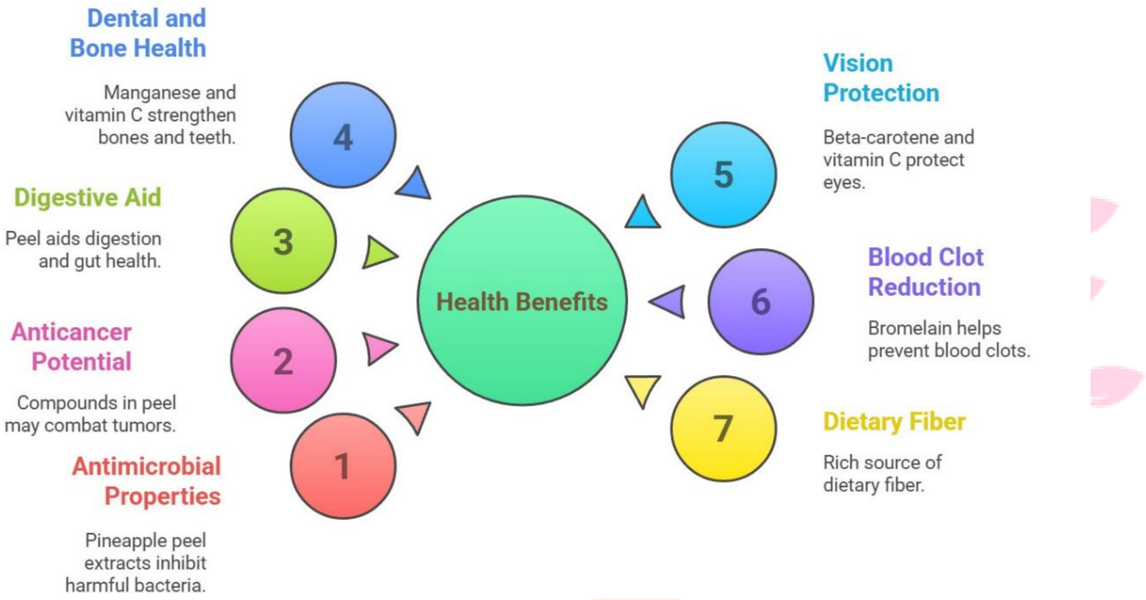

Figure 3

Pineapple peel isn't just waste—it actually packs a punch when it comes to health benefits. From boosting digestion and strengthening bones to offering anticancer and antimicrobial properties, this tough outer layer supports overall wellness. It even helps with vision protection, reduces blood clot risks, and is a great source of dietary fiber.

It's worth noting that pineapple peel consists of significant dietary fiber content [1-3, 9, 15, 20, 23, 34]. Dietary fibre plays a crucial role in maintaining good bowel health, regulating blood glucose levels, and reducing the risk of heart diseases [1, 34]. Pineapple peel has been found to have a higher total dietary fibre content compared to some other fruits [1].

To harness these valuable compounds, various extraction techniques have been explored, ranging from traditional solvent extraction methods to more modern, environmentally friendly approaches like ultrasound and microwave-assisted extraction [1-2, 5-6, 15-16, 23]. These greener extraction techniques need lower amounts of solvent while producing products in shorter time spans to obtain bioactive compounds effectively [2, 5-6].

The discarded parts of pineapples known as peel contain various beneficial compounds which show antioxidant activity as well as anti-inflammatory properties and potential detoxification function. Its rich composition of phenolics, flavonoids, bromelain, and dietary fibre, along with its potential antimicrobial and anticancer properties, underscores its value as a novel food ingredient and a contributor to the waste-to-wealth paradigm [1-3, 6, 9, 15, 23, 25-26]. Further research into its applications and the optimization of extraction methods will undoubtedly unlock even more of its potential benefits for human health and environmental sustainability.

Sustainable Waste Management of Pineapple Peel in Food and Beverage Industry

The ever-pressing matter of waste, and within the vibrant food and beverage industry, pineapple peel presents a fascinating case study in sustainable management. What was once discarded as a problematic residue is now being recognized for its inherent value, offering both significant challenges and exciting opportunities for a more circular approach [2-4, 6, 14-15, 19, 25-26]. Delving into the intricate landscape of managing this abundant resource reveals both the challenges and opportunities associated with its sustainable utilization:

Challenges and Opportunities in Sustainable Pineapple Peel Waste Management

The sheer volume of pineapple peel generated by the F&B sector presents a significant problem in itself. Globally, millions tonnes of pineapple are produced annually [2, 3, 15], and with processing often resulting in *40-50% of the fruit's weight becoming peel waste* [2, 15-16, 25-26], the scale of disposal is immense [3, 4, 16].

Challenges

Bulk and Perishability: With over 80% moisture content, pineapple peel is highly perishable, making its handling and storage difficult [6, 14, 25-26].

Lack of Infrastructure and Awareness: In many developing economies, there may be a lack of adequate infrastructure and policy support for large-scale sustainable waste management and valorization technologies [4, 35-37]. Furthermore, limited awareness among stakeholders regarding the potential economic and environmental benefits of pineapple peel valorization can hinder adoption of sustainable practices [35-37].

Variability in Composition: The exact chemical composition of pineapple peel can vary depending on the pineapple variety, maturity stage, and processing methods [2, 4, 11, 15-16, 26], which can impact the efficiency and suitability of different valorization technologies [25-26, 38].

Technological and Economic Feasibility: While numerous valorisation technologies exist, scaling these up to an economically feasible and industrially relevant level can be challenging [2-4, 6, 25-26, 36, 38, 39]. Initial investment costs, operational efficiency, and market demand for the end products all play crucial roles [2, 3, 6, 25, 35, 36, 38, 39].

Safety Concerns: When valorising food waste for reuse in the food chain (either human or animal), ensuring quality and safety by addressing potential microbial contamination, organic residues, or the formation of undesirable substances during processing is paramount [2, 24].

Opportunities

Abundant and Renewable Resource: The sheer volume of pineapple peel generated makes it an abundant and readily available renewable resource [2, 3, 4, 14, 15, 16, 25, 26, 35], offering a consistent feedstock for various valorization processes [2, 3, 4, 15, 25, 26, 35].

Rich in Bioactive Compounds: Pineapple peel is a treasure trove of valuable bioactive compounds [1-6, 9-11, 14-16, 20, 23, 25-26], including phenolic compounds (antioxidants) [1-6, 9-11, 14-16, 20, 23, 26], dietary fiber [1-3, 9, 15, 20, 23, 26, 34], and bromelain (proteolytic enzyme) [1-3, 9, 15, 20, 23, 26, 34], all of which have significant applications in the food, beverage, nutraceutical, pharmaceutical, and other industries [1-6, 14, 16, 25-26].

Circular Economy Potential: Valorizing pineapple peel aligns perfectly with the principles of the circular economy [2-3, 6, 15, 24-26, 35-39], the technology transforms waste flows into beneficial products while decreasing dependence on new original materials while minimizing damage to the environment [2-3, 6, 15, 24-26, 35-39]. This can enhance the sustainability credentials of the food and beverage industry.

Economic Benefits: Converting pineapple peel waste into value-added products can create new revenue streams for the industry, reduce waste disposal costs, and potentially lead to the development of new businesses and employment opportunities [2-4, 6, 14-15, 25-26, 35-39].

Environmental Sustainability: Sustainable management of pineapple peel waste through valorization can significantly reduce the carbon footprint of the food and beverage industry by diverting waste from landfills, reducing greenhouse gas emissions, and potentially producing bioenergy [2-4, 15, 25-26, 35-39].

Technological Advancements: Ongoing research and development are continuously yielding new and cutting-edge technologies for the productive and economical extraction and conversion of essential compounds from pineapple peel [2-6, 15-16, 23, 25-26, 35, 38], including greener extraction methods [2, 4-6, 15-16, 23, 25].

Policy Drivers and Consumer Demand: Increasing environmental regulations, stricter waste management policies, and growing consumer demand for sustainable and natural products are creating a favourable environment for the adoption of pineapple peel valorization strategies [2, 3, 15, 24, 25, 35, 36, 37].

Applications of Pineapple Peel in Food and Beverage Industries

The inherent properties of pineapple peel make it a versatile resource for various applications within the food and beverage sector, contributing to its sustainable management by transforming waste into valuable ingredients and products:

Dietary Fiber Source: The high level of total dietary fibre (TDF) exists in pineapple peel alongside insoluble and soluble portions [1-3, 9, 15, 20, 23, 26, 34], makes it an excellent ingredient for fiber enrichment in various food products like bakery goods, extruded snacks, and yogurts [1, 3, 15, 17, 20-21, 23, 26, 30].

Natural Antioxidant Ingredient: The rich array of phenolic compounds and flavonoids in pineapple peel [2-6, 11, 14-16, 20, 23, 25, 26]. They can be incorporated into edible coatings for fresh produce, beverages, and various food products [2, 13, 15, 20, 24].

Bromelain Source: Pineapple peel is a significant source of the valuable proteolytic enzyme bromelain [1-6, 14, 16, 25-26]. Bromelain extracted from the peel can be used as a natural meat tenderizer [1, 15, 25], in baking applications, and potentially as a functional ingredient with anti-inflammatory and other health-promoting properties [1, 3, 6, 12, 25].

Production of Organic Acids: The elevated sugar levels in pineapple peel [2, 3, 4, 16, 25, 26] makes it a compatible substrate for fermentation processes to generate different organic acids like acetic acid, citric acid, and lactic acid [1-6, 14-16, 25-26, 38]. These acids have wide-ranging applications as food preservatives, flavour enhancers, and acidity regulators in the F&B sector [1, 3, 15, 25, 38]. Pineapple peel can be used to produce vinegar through a two-stage fermentation process [3, 15, 16, 22, 23, 25].

Natural Flavor and Aroma Compounds: Pineapple peel contains various volatile compounds such as esters, aldehydes, and ketones that contribute to its characteristic fruity aroma and flavor. These can be extracted and potentially used as natural flavoring agents in food and beverage products [2, 15, 16, 23, 25].

Prebiotic Ingredient: The fiber and other carbohydrate components of pineapple peel can potentially act as **prebiotics**, promoting the growth of beneficial bacteria in the gut and contributing to digestive health [1, 3, 15, 23, 34].

Natural Colorant: Pineapple peel contains carotenoids and other pigments, which could potentially be extracted and used as natural food colorants [11, 14-16].

Substrate for Enzyme Production: Pineapple peel can serve as a low-cost substrate in fermentation processes for the production of various other enzymes like β-glucosidases and pectinases, which have applications in the F&B sector [1, 3, 6, 14-16, 23].

By strategically focusing on these applications, the food and beverage industry can not only address the challenges associated with pineapple peel waste but also unlock significant economic and environmental benefits, moving towards a more sustainable and circular model of production and consumption [2, 3, 6, 15, 24, 25, 26, 35, 36, 37, 38, 39].

Forthcoming Possibilities and Research Pathways

The future prospects for incorporating pineapple peel as a potential ingredient in detox drink formulations are promising, driven by its rich profile of bioactive compounds and the growing consumer inclination towards natural and health-enhancing beverages. Research indicates that pineapple peel, often a significant component of food waste [2-3, 20], is a treasure trove of phytochemicals exhibiting notable antioxidant and anti-inflammatory properties [1, 3, 11, 20, 25]. These inherent characteristics position pineapple peel extracts as compelling candidates for innovative detox drink formulations.

Innovations in Detox Drink Formulation

Recent advancements in detox drink formulations focus on enhancing the bioavailability and functionality of pineapple peel's bioactive compounds. Traditional extraction techniques are being replaced by more efficient and eco-friendly methods. These technologies have demonstrated higher yields of phenolic compounds and antioxidants while reducing processing time and solvent consumption [2-3, 5]. Additionally, solid-state fermentation (SSF) using microorganisms like *Lactobacillus rhamnosus, Aspergillus oryzae, and Lactobacillus plantarum* has been shown to improve the liberation of bound phenolics, leading to the formation of novel bioactive metabolites that further boost the detoxifying potential of the extracts [2-3, 20].

To improve stability and functionality, encapsulation techniques such as spray drying are being explored. Encapsulation with agents like maltodextrin helps protect sensitive compounds, such as phenolics and vitamin C, from degradation during processing and storage, ensuring their efficacy in the final product [2, 13, 20, 25]. Furthermore, future detox drink formulations may incorporate synergistic blends by combining pineapple peel extracts with ingredients like ginger, mint, and citrus peels, offering enhanced detoxification and wellness benefits [31-32, 40].

Potential Market Trends and Consumer Demand

The demand for detox drinks infused with pineapple peel aligns with several prevailing market trends. Increasing consumer awareness about health and wellness has fueled interest in natural beverages that support detoxification, immune function, and overall vitality [3, 31-32, 40]. Moreover, there is a clear preference for natural and plant-based ingredients, with consumers gravitating towards "clean label" products that avoid synthetic additives [32, 40].

Sustainability concerns are also driving interest in food waste valorization. Utilizing pineapple peel in functional beverages supports circular economy principles and resonates with environmentally conscious consumers who prioritize waste reduction and sustainable consumption [2-3, 17, 40]. Additionally, the market for innovative flavors and functional beverages continues to expand, with consumers seeking unique taste experiences and drinks that offer targeted health benefits. Pineapple peel extracts contribute both distinctive flavors and bioactive properties, making them a valuable addition to this evolving market [32, 40].

Future Research Directions

To fully harness the potential of pineapple peel in detox drink formulations, several key research areas require further exploration. While its antioxidant and anti-inflammatory properties are well-documented [1, 3, 11, 20, 25], more studies are needed to understand its specific detoxifying effects on liver function, toxin elimination, and gut health [24, 28-29].

Ensuring the bioavailability and stability of pineapple peel-derived compounds in detox drinks is another critical aspect. Research into advanced encapsulation techniques, enzymatic activation, and structural modifications could further enhance their functional benefits [2, 13]. Safety assessments, including toxicological studies and contaminant screening, will be necessary to establish regulatory guidelines for the commercial use of pineapple peel-based ingredients [24].

Consumer acceptance plays a pivotal role in market success. Since taste and aroma significantly influence purchasing decisions, sensory evaluation studies will be essential in developing palatable detox drinks with pineapple peel extracts [17, 32]. Finally, transitioning from laboratory-scale research to large-scale industrial production poses challenges such as cost-effectiveness, process efficiency, and equipment availability. Addressing these factors will be key to successfully commercializing pineapple peel-based detox drinks [2-3].

The integration of pineapple peel into detox drink formulations presents an exciting opportunity to develop sustainable, health-promoting beverages. By focusing on optimizing extraction techniques, understanding bioactivity mechanisms, ensuring safety, and catering to consumer preferences, researchers and industry stakeholders can unlock the full potential of this valuable agricultural by-product. Continued innovation in this field will contribute to both environmental sustainability and the growing demand for functional beverages.

Conclusion

In a world grappling with environmental degradation and unsustainable consumption, the valorization of agro-industrial waste emerges not only as a necessity but as an opportunity for innovation and responsible resource utilization. This review underscores the immense potential of pineapple peel – an often-overlooked by-product of fruit processing – as a functional, sustainable, and health-promoting ingredient for detox drink formulations.

Through a comprehensive exploration of its nutritional richness and bioactive composition, pineapple peel has been shown to contain high levels of dietary fiber, phenolic compounds, flavonoids, essential vitamins, minerals, and the proteolytic enzyme bromelain. These components are strongly associated with antioxidant, anti-inflammatory, antimicrobial, and potential detoxifying properties. Beyond their physiological benefits, these compounds also provide opportunities for product diversification in the functional beverage market, particularly in formulations aligned with the current demand for clean-label, plant-based, and health-focused products.

The environmental imperative is equally compelling. The global pineapple industry generates millions of tonnes of waste annually, with peel accounting for a substantial proportion. Leveraging this by-product in high-value applications offers a dual advantage: mitigating the environmental burden of organic waste while creating circular economic value. The transformation of pineapple peel into a resource exemplifies the principles of sustainable development and supports the transition to greener food and beverage systems.

However, while the prospects are promising, actualizing this potential requires a multifaceted approach. Pineapple peel compounds demonstrate improved functionality and shelf-life through recent breakthroughs in green extraction techniques and both encapsulation techniques as well as solid-state fermentation methods. Yet, challenges remain – particularly concerning large-scale industrial scalability, consumer acceptance, regulatory compliance, and consistent bioactive retention during processing.

Research should concentrate on developing a clear understanding of how pineapple peel compounds work to detoxify the body, optimizing integrated bioprocessing techniques, and conducting sensory evaluation trials to ensure product palatability and market readiness. Establishing robust safety profiles and standardization protocols will also be critical to ensuring consumer trust and regulatory approval.

Ultimately, the repurposing of pineapple peel into functional detox beverages is not merely a novel formulation strategy – it is a testament to how innovation, science, and sustainability can intersect to redefine waste as wellness. Embracing this paradigm shift can inspire broader transformations across the agri-food sector, setting a precedent for waste-to-value innovation and contributing to global health and environmental resilience.

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Abbrevations:

PPW – Pineapple Peel Waste

F&B – Food and Beverage

FAO – Food and Agriculture Organization

w/w – Weight per weight

DPPH – 2,2-diphenyl-1-picrylhydrazyl

ABTS - Trolox equivalent antioxidant capacity

CUPRAC - CUPric Reducing Antioxidant Capacity

TDF – Total Dietary Fibre

IDF – Insoluble Dietary Fibre

SDF – Soluble Dietary Fibre

TPC – Total Phenolic Content

GAE/g - Gallic acid equivalent/gram

UAE – Ultrasound Assisted extraction

MAE – Microwave Assisted Extraction

TFC – Total Flavonoid Content

QE/g – General Electric/gram

FRAP – Ferric Reducing Antio

EDTA – Ethylenediaminetetraacetic Acid xidant Power Assay

pH – Potential of Hydrogen

IBS – Irritable Bowel Syndrome

SSF – Solid State Fermentation

Conflict of Interest: The authors have declared no conflicts of interest.