

Review

Recent Updates on the Conversion of Pineapple Waste (*Ananas comosus*) to Value-Added Products, Future Perspectives and Challenges

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Abstract: Pineapple waste accounts for a significant part of waste accumulated in landfill which will further contribute to the release of greenhouse gases. With the rising pineapple demands worldwide, the abundance of pineapple waste and its disposal techniques are a major concern. Exploiting the pineapple waste into valuable products could be the most sustainable way of managing these residues due to their useful properties and compositions. In this review, we concentrated on producing useful products from on-farm pineapple waste and processing waste. Bioenergy is the most suitable option for green energy to encounter the increasing demand for renewable energy and promotes sustainable development for agricultural waste. The presence of protease enzyme in pineapple waste makes it a suitable raw material for bromelain production. The high cellulose content present in pineapple waste has a potential for the production of cellulose nanocrystals, biodegradable packaging and bio-adsorbent, and can potentially be applied in the polymer, food and textile industries. Other than that, it is also a suitable substrate for the production of wine, vinegar and organic acid due to its high sugar content, especially from the peel wastes. The potentials of bioenergy production through biofuels (bioethanol, biobutanol and biodiesel) and biogas (biomethane and biohydrogen) were also assessed. The commercial use of pineapples is also highlighted. Despite the opportunities, future perspectives and challenges concerning pineapple waste utilisation to value-added goods were also addressed. Pineapple waste conversions have shown to reduce waste generation, and the products derived from the conversion would support the waste-to-wealth concept.

Keywords: pineapple; waste; conversion; utilisation; value-added product



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1. Introduction

The concern on sustainable waste management for agricultural and food processing waste has been increasing recently. These wastes often end up in landfills, where a significant volume of waste is converted into greenhouse gases (GHG) and methane. The particular reason for the circumstances is that these wastes are easily degraded compared to other wastes. Thus, appropriate waste management techniques should be implemented to reduce the release of harmful substances to the environment. In line with United Nations' Sustainable Development Goal (SDG), with good food waste management practice, responsible production and consumption by connecting the concept of food loss and waste (FLW) management could be achieved [1–3]. In recent decades, researchers have been concentrating on the conversion of agricultural and food waste to valuable products based

on the waste-to-wealth concept to reduce the drawbacks of improper waste management techniques [4–7]. Pineapple is one of the most produced fruits, of which Costa Rica, Philippines, Brazil, Thailand and India are the primary pineapple producers [8]. Cultivated in tropical and subtropical zones, pineapple belongs to the Bromeliaceae family and has a unique shape with wide leaves and fruits that differentiates them from other monocotyledons plants [9]. Besides, pineapple has 47.8 mg of vitamin C and 13 mg of calcium per 100 g of pineapples. There has been a growing demand for pineapple fruits and products for the past few years. A massive amount of waste was produced as the consequences of world demand. The wastes are generated not only from the freshly consumed fruits, commercialised juice, and canned and frozen products but also from the harvesting and processing practices [10]. As mentioned above, the utilisation of waste is the most sustainable way of handling wastes. Considering its characteristics, composition and health benefits, pineapple waste contains proteolytic enzyme for bromelain production [11] and phenolic compound which is a good antioxidant source including antimicrobial and anticancer properties [12]. Pectin, lignin, cellulose and their derivatives from pineapple waste are the major components needed in producing nanocellulose and green packaging [13–15]. Since pineapple waste is a good carbon source, organic acid [16], wine [17], vinegar [18], dye adsorbent [19], biofuel [20–22] and biogas [23–25] can be produced from it. The properties and characteristic of waste feedstock are crucial factors that need to be understood before the conversion. There are many aspects that researchers need to take into consideration in the production and development of the mentioned value-added product involving productivity, purity, stability and also suitability to be marketed at the industrial level. By taking advantage of the pineapple's composition for the utilisation of non-edible parts, it is remarkably important to select the most suitable and cost-effective method to produce a higher yield of these products to meet the market demand. The development of pineapple waste to bioenergy seems to be the most sustainable way to minimise fossil fuel dependency. Thus, the overall purpose of this review is to provide a comprehensive overview of pineapple's commercial use, waste production, characteristics and composition of pineapple waste and pineapple waste conversion value-added products. With these findings, pineapple producers and researchers may gain fundamental knowledge to explore new perspectives for sustainable ways in managing pineapple by-products.

2. Global Production

Being the third most-produced tropical fruit after banana and mango [26], the pineapple was initially domesticated from Brazil and Paraguay in the Amazon basin of South America [27]. Pineapple is recognised due to its scent, taste, juiciness and sweetness. There are numerous pineapple varieties based on their colours, shapes, sizes and flavours [8]. Figure 1 shows the pineapple structure that consists of stem, leaves, crown, roots and multiple fruits that evolved from the combination of individual fruitlets on a sole stalk. Pandit et al. [28] reported that Smooth Cayenne, Queen, Spanish and Abacaxi are the four primary pineapple categories. Among the number of varieties that exist, Smooth Cayenne is the most marketed variety [29]. Some of the other pineapple varieties are 'Moris', 'N36', 'Sarawak', 'Gandul', 'Yankee', 'Josapine', 'Maspine' and 'MD2' [8,30]. Malaysia is also known as one of the pineapple exporters in Southeast Asia. As stated by the Malaysian Pineapple Industry Board (MPIB) in 2018, Malaysia exported about 42,129 metric tons of pineapple from a cultivation area of 16,653.55 hectares with Johor, Sarawak and Selangor as the primary producer of Malaysian's pineapple [31]. Furthermore, 'Moris', 'Josapine', 'N36' and 'MD2' are the most produced pineapple varieties in Malaysia, at 27.52%, 24.7%, 20.63% and 15.82% of total production, respectively. According to Hossain [27], the demand for 'MD2' pineapple variety has influenced the pineapples' global trade by 80%. The 'MD2' is also recognised by the names 'Golden Ripe', 'Super Sweet', 'Rompine' or 'Gold' and is sweeter, has low acidity and fibre, is smaller and contains four times more vitamin C than others [32].

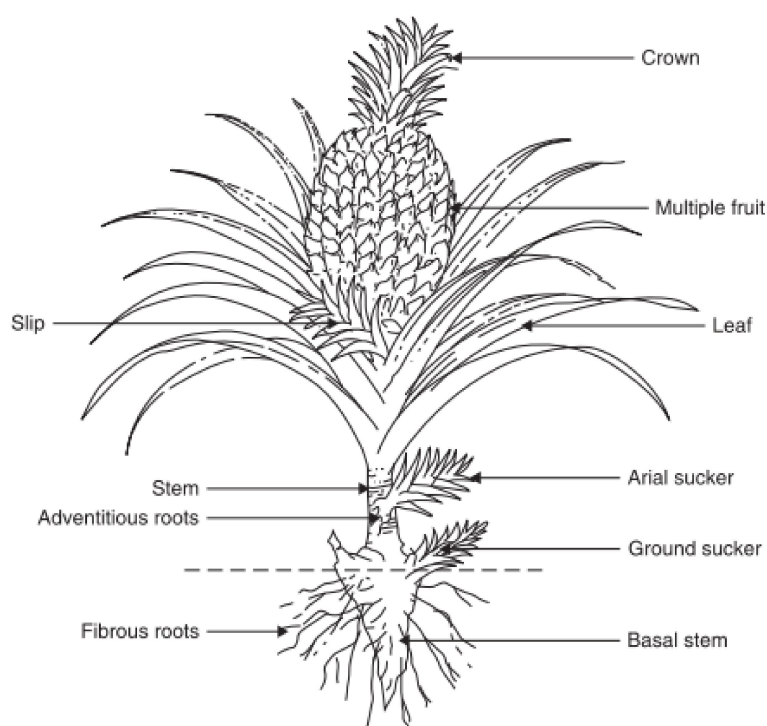


Figure 1. Morphological structure of the pineapple (adapted from Hassan et al. [33]).

Pineapple is cultivated extensively in several tropical and subtropical countries globally, such as Thailand, Malaysia, Philippines, Costa Rica, Brazil and Kenya [6,29]. According to Food and Agriculture Organization (FAO), world pineapples production in 2019 increased to 28,179,348 tonnes compared to 28,430,017 tonnes in 2018 [34]. While in Southeast Asia, Philippines exported the highest numbers of pineapples, followed by Malaysia and Thailand in 2018. The major export commodities of processed pineapple are canned pineapple, juice and concentrated juice; as stated by FAO [34], Thailand exported the most canned pineapple while Costa Rica exported the most pineapple juice in 2018 as shown in Table 1.

3. Commercial Use of Pineapple

Generally, pineapple fruits are consumed fresh by removing the pulp and cutting the pulp to pieces and are also commercialised into processed products. Processed pineapple products include juice, canned pineapple, cocktail, jams, wines, powder, frozen pineapple and fruit punch [8,27,33]. Canned pineapple products are the most popular processed pineapple products that are usually used in main dishes and salad, as well as appetisers, beverages and desserts, and they have a long shelf life [35]. Processes such as washing, trimming, slicing and cooling are involved in canned pineapple processing as presented in Figure 2. Other than canned pineapple, pineapple juice is one of the major pineapple-based products.

Table 1. Main exporting countries of processed pineapple products under the form of canned, juice and concentrated juice in 2018 (data extracted and modified from FAO [34]).

Canned	Export Unit (Tonnes)	Juice	Export Unit (Tonnes)	Concentrated Juice	Export Unit (Tonnes)
Thailand	477,224	Costa Rica	150,596	Philippines	111,483
Philippines	221,287	Netherlands	105,742	Thailand	109,847
Indonesia	185,466	Belgium	18,456	Netherlands	59,391
Kenya	30,154	Germany	12,556	Indonesia	29,143
Netherlands	28,122	Philippines	11,201	Costa Rica	27,496
Germany	14,822	Cyprus	9195	Kenya	14,875
Viet Nam	14,359	Mexico	4683	South Africa	10,232
China	10,954	Nepal	4626	Brazil	3348
Singapore	8297	Austria	3954	United States of America	2155
United Arab Emirates	7528	Guatemala	3825	Spain	1900
Eswatini	6396	France	3447	Eswatini	1456
United States of America	4661	Benin	2977	Lebanon	1403
Malaysia	3726	El Salvador	2919	France	1330
France	3103	Ireland	2825	Ghana	1269
Spain	3623	Honduras	1955	Germany	1260

Pineapple undergoes several processes to preserve the juice by eliminating microorganisms and chemical modifications [36]. Several attempts have been made to increase the quality of pineapple juice by using different processes such as reverse osmosis [37], high pressure, ultrasound and pasteurisation [38], and carbonation of pineapple juice that will help prolong its shelf life. Jori et al. [39] who investigated the pineapple juice's potential as carbonated drinks found that a carbonated drink with 15% juice concentration in it has a period of about nine weeks of storage. The authors found that the carbonated pineapple juice can last for about three months without the taste changing. Pineapple jam is one method of preserving pineapple for long periods by boiling the crushed pineapple pulps with water, sugar and preservatives. Colouring and flavouring were added to improve the taste and quality of the jams. However, this conventional production method requires a long time and causes a drop in their nutritional values [40,41]. Fortification of the nutritional ingredients in pineapple jams has proven to increase its nutrient content and taste [42,43]. Pineapple is also being transformed into confectionery products such as candy. Pineapple candy is prepared by combining sugar syrups with pineapple juice or syrups and dried to form the candy. Few studies have reported the development of pineapple candy on its storage period, sugar concentration as well as its drying method [44–46]. Pineapple powder is a useful pineapple-based product because it has a long shelf life and can be used as a food additive and flavouring. Through the dehydration process, where moisture is removed from the fruits, pineapple powder is obtained. Various drying techniques to produce pineapple powder have been reported such as oven drying [47], spray drying [48,49] and foam mat drying [50]. Pineapple powder has also been utilised as a food additive and flavouring [51], in biscuits [52] and in milk [53].

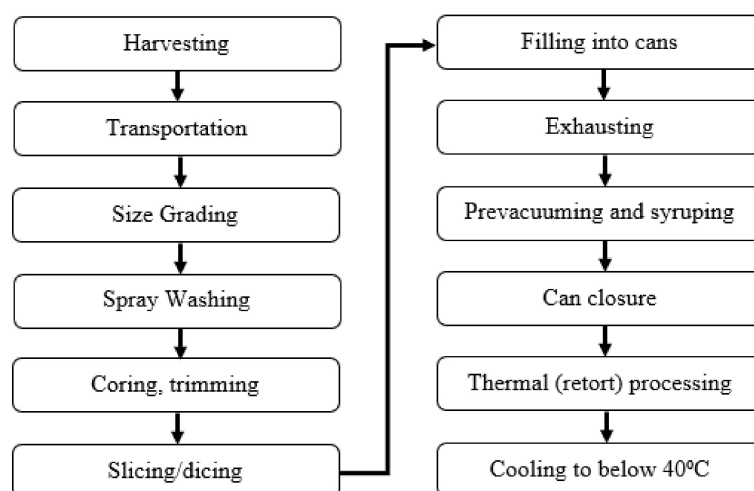


Figure 2. Pineapple canning process (adapted and modified from Downing [54] and Siow and Lee [35]).

4. Waste Production from Pineapple Waste

Increasing demand for pineapple contributes to an enormous pineapple production, and as a consequence, a large amount of waste is generated. About 80% of pineapple parts, including the crown, peels, leaves, core and stems, are discarded during pineapple processing, transportations and storage and ends as waste [10,55]. As one of the leading agricultural commodity producers in the Southeast Asian region [56], Malaysia produces 335,488 tons of pineapple in addition to 67,098 and 137,550 tons of leaf and peel wastes [57]. These wastes contain high moisture, sugar, albumins, lipids and vitamins that are prone to microbial spoilage thus contributing to environmental problems [6,58]. The abundance of these wastes means they often remain relatively unexploited and are often subjected to the landfill [59]. The increasing amount of waste in the landfill causes severe environmental problems since this waste will inhibit biological and chemical oxygen demand of ecosystems [60], site contamination and increase the risk of infectious diseases [10]. Traditionally, these wastes were subjected to open burning as waste management technique, but this contributes to air pollution [61]. Landfilling, incineration, pyrolysis and gasification, composting and anaerobic digestion are common techniques in managing these wastes [62]. However, the large capital cost required to dispose of these wastes and land contributes to greenhouse gas emissions [63]. These wastes can be converted into valuable products through various biochemical (microbial fermentation and anaerobic digestion), thermochemical (pyrolysis, gasification, combustion and incineration) and physicochemical (transesterification) processes to generate energy and bioproducts [64–66]. A biochemical process, using pineapple waste as feedstock source in biogas plants, seems to be one of the dynamic approaches to improve the utilization and management levels of this waste especially in rural areas [67–69]. Bioenergy through an anaerobic digester plant would be practical on on-site pineapple growing areas, especially rural areas where connection to energy supply is limited [68]. Pineapple waste is a potential feedstock for biodegradable material production due to the presence of its fibre [70]. The presence of aromatic compounds inside pineapple waste such as 2-heptanol, propanol and 3-hexanone increases the possibility to turn these wastes into essential oil [71]. High sugar content, antioxidants, bioactive compounds and bromelain enzyme and the presence of carbonyl, carboxyl and hydroxyl groups, as well as the abundance of lignin, hemicellulose and cellulose, inside pineapple by-products have increased the potential of utilising these wastes for acid, bromelain, adsorbent as well as biofuel and biogas production. Utilising these wastes to produce value-added product is one of the sustainable ways of managing these wastes.

5. Characteristics and Composition of Pineapple Waste

It is essential to know the composition and characteristics of pineapple waste before converting them to valuable products. The identification of major polyphenolic compounds from pineapple waste amounts to 31.76 mg of gallic acid, 58.51 mg of catechin, 50 mg of epicatechin and 19.5 mg of ferulic acid per 100 g of dry extracts [72]. Recent research by Dahunsi [23] observed that pineapple waste contains 19.4% lignin, 32.4% cellulose and 23.2% hemicellulose. According to the author, untreated peels contain 4.26 g/kg TS of potassium, 339.4 g/kg TS of calcium and 0.013 g/kg TS of magnesium. Khedkar et al. [22] reported the amount of crude fibre, fat and proteins from pineapple peels as 23.71%, 0.46% and 0.33%, respectively. Pineapple leaf waste contains 13.05% lignin, 21.02% hemicellulose and 41.15% cellulose [73]. The high content of lignin, cellulose and hemicellulose in pineapple waste makes them suitable as feedstocks to produce fermentable sugar for energy production. Other than that, carbonyl, carboxyl and hydroxyl groups from pineapple waste can be used as a precursor in the preparation of activated carbon [74]. Pardo et al. [70] investigated the amount of protein, ash and fibre from different pineapple parts, and the results showed that pineapple pulp contains the highest protein and fibre. While leaf has the lowest amount of protein, it contains a high amount of ash. According to the authors, pineapple peel contains the highest fibre amount compared to pulp, leaf and core. In addition, pineapple leaf has a high amount of lignin and cellulose compared to others. According to Campos et al. [29], new products could be produced from pineapple since it contains vitamin C, polyphenols, dietary fibre and simple and complex sugars. Other than that, pineapple leaf from the 'MD2' variety contains 43.43% carbon whereas the stem contains 41.09% carbon [75]. Pineapple waste also contains a proteolytic enzyme named bromelain. Nor et al. [76] observed that the specific enzyme activity from various parts of pineapple waste and extract from pineapple flesh showed the highest specific enzyme activity of 561 CDU/mg protein. Pineapple waste also contains 4% polyphenols and 55% reducing sugar from a total of 82% of total sugars [77]. Solid pineapple waste comprises of 11.74% glucose, 9.70% fructose, 2.93% xylose, 2.05% sucrose and 24.04% reducing sugars [16].

6. Conversion of Pineapple Waste to Value-Added Products

Pineapple's composition, including high sugar content, trace elements (potassium, calcium and magnesium) and polyphenolic compound, has raised the interest in converting these wastes to valuable products. Pineapple can be utilised in the production of various valuable products including nanocrystals, bromelain enzyme, bioactive compound, wine, vinegar, biopolymer, bio-packaging, organic acid, adsorbent, biofuel and biogas. Previously, pineapple waste has also been utilised to form phenolic antioxidants, anti-dyeing agents and animal feed [27,78]. Several studies focusing on converting waste from pineapple are discussed.

6.1. Bio-Based Byproduct and Final Product

This section lists some conversions of pineapple waste into bio-based by-products such as cellulose nanocrystals (CNC), bromelain enzyme and bioactive compounds and final bio-based products such as organic acid, wine and vinegar.

6.1.1. Cellulose Nanocrystals

Cellulose nanocrystals (CNC) derived from the abundance of cellulose in the biomass are one of the most favourable materials for nanocomposites. Currently, CNC serve as a reinforcing agent in the nanocomposites field. CNC have a large surface area, high mechanical strength, are non-toxic, hydrophilic, biocompatible and biodegradable [79,80]. According to Brinchi et al. [81], the nanocomposites' mechanical and barrier properties improved when a CNC was applied as filler. Due to the high amount of cellulose from pineapple waste, there is an emerging interest in isolating CNC from pineapple waste for various applications. The CNC isolated from pineapple leaves waste showed improvement in the mechanical properties of natural rubber when the isolated CNC were used as

reinforcing fillers [82]. The natural rubber reinforced with CNC showed good chemical resistance and tensile strength. Anwar et al. [83] studied the properties of nanocrystal produced from pineapple peel waste juice and compared its properties with bacterial cellulose. The comparison with bacterial cellulose revealed that isolated nanocrystals have the same chemical composition and better thermal stability as bacterial cellulose but differ in their crystallinity. The X-ray Diffraction analysis showed that nanocrystals have a more allomorph structure with an 89% crystallinity index. A high crystallinity index (>70%) increases thermal stability and bacterial resistance [84]. The crystallinity index from CNC isolated from pineapple waste from Pereira et al. [85] (92.13%) and Chawalitsakunchai et al. [82] (92.95%) exhibited higher crystallinity than other agricultural wastes such as 72% from sago seed shell [86], 77.96% from passion fruit [87] and 74.1% from cucumber waste [88]. However, several studies reported lower values such as 73% in [80] and 73% in [13]. However, the value is still comparable to that of other wastes since the crystallinity index value exceeded 70%. In addition, the morphological structure and thermal stability of cellulose extracted from PALF improved by isolation using Steam-Alkaline coupled treatment [89]. According to the authors, isolated cellulose was able to withstand high temperatures. At the same time, hydrolysis of hemicellulose and lignin were improved, and defibrillation to microfibril occurs due to the steam-alkaline coupled treatment. Isolation of CNC from pineapple crown wastes using chemical treatment followed by acid hydrolysis results in CNC having high crystallinity index, thermal degradation and hydrophilicity [13]. Earlier, CNC extracted from pineapple peel is small in size and has increased variability and negative zeta potential values [79]. The CNC extracted from pineapple peel for 30 min offered high thermal stability (225 °C) and crystallinity, and thus, it held great potential as reinforcement in the manufacturing of nanocomposites [80]. In this regard, several works have been undertaken isolating CNC from pineapple waste [85,90,91]. However, additional work should be conducted to explore the potential application of CNC isolated from pineapple waste in various fields such nanocomposites, medical and biosensors.

6.1.2. Bromelain Enzyme

Bromelain, a type of proteolytic enzyme, has been found in pineapple. Bromelain helps the digestion process and is essential in various applications. The main protease that exists in the bromelain enzyme is identified as stem bromelain (EC 3.4.22.32) and fruit bromelain (EC 3.4.22.33) [76]. Composition, enzyme and antioxidant activities of bromelain extracted from three different pineapple varieties showed that stem extract contains higher bromelain activity than peel and flesh. In contrast, peel and stem extract contain higher reducing sugar and soluble fibre [92]. Earlier, Nor et al. [76] obtained bromelain from pineapple crude waste mixture with a considerable amount of specific enzyme activity. However, it needs to be purified further to meet the market's requirement. In a different study by Nor et al. [93], bromelain was purified by two-stage ultrafiltration using different tubular ceramic membranes. The appropriate transmembrane pressure and crossflow velocity were applied to ensure high enzyme recovery and purity fold. Then, the two-stage foam fractionation of bromelain achieved a high specific activity of 165.6 U/mg with a recovery of 45.2% [94]. The purification of bromelain by aqueous micellar two-phase systems with ionic liquids acting as co-surfactants showed a high bromelain recovery of above 90% [95]. The study by Wu et al. [96] showed that an aqueous biphasic system is a possible bromelain recovery method as it has shown a higher purification fold of 16.3. Additionally, separation of bromelain by membrane separation techniques and further stabilisation by freeze-drying were able to increase the protein concentration two-fold to 21.0 mg protein/mL [97]. In another study, the crude juice of pineapple stem and peels was able to recover 80% to 90% of bromelain [11]. According to Misran et al. [98], pineapple peels contained higher bromelain activity compared to flesh. To date, few researchers have addressed the function of bromelain in various applications. The absorption of bromelain using probiotic *Bacillus* sp. was able to stabilise the bromelain for therapeutic application [99]. Moreover, cross-linked bromelain can be used for industrial applications

such as cleansing agents and fabric industries [100]. Extracted bromelain from pineapple waste is also effective as acne treatment as it exhibits a high inhibitory effect towards common skin pathogens [101]. This study revealed that facial cleansers containing the purified bromelain are highly sensitive towards *Staphylococcus aureus* and *Propionibacterium acnes*. Moreover, the study revealed potential bromelain use in protecting rats from disease caused by aluminium [102].

6.1.3. Bioactive Compound

Pineapples and their wastes serve as a good source of antioxidants. The formation of free radicals caused by the oxidation of biological molecules can be prevented by an antioxidant, for example, a phenolic compound which has antioxidant, antimicrobial and anticancer properties [12]. Sepúlveda et al. [77] reported that the extraction of pineapple waste using the autohydrolysis process resulted in obtaining polyphenols with high antioxidant activity. The study also revealed that pineapple waste is a good source of antioxidants compared to readily available antioxidants in the market, and all pineapple waste extracts showed higher antioxidant activity. The potential of pineapple waste as an antioxidant and anticancer was evaluated by Rashad et al. [103], where the methanolic extract of fermented pineapple waste contained high levels of phenolic content at 20 mg gallic acid/100 g dry waste. However, a study by Othman et al. found that the phenolic content in pineapple peels was lower than in banana peels [104]. Another study by Mathew et al. [105] reported that phenolic antioxidant compounds in pyroligneous acid from pineapple waste is suitable for use in broad applications. According to Li et al. [72], the main polyphenolics in pineapple peels were gallic acid, ferulic acid, catechin and epicatechin with 0.32 mg/g, 0.20 mg/g, 0.59 mg/g and 0.5 mg/g, respectively. This study's gallic acid and catechin values were higher than the highest value obtained from grape waste [106]. The highest gallic acid and catechin obtained were only 0.236 mg/g for gallic acid and 0.247 mg/g for catechin. In contrast, mango peels contain 28.6 to 43.1 mg gallic acid per 100 g of dry extract [107]. These values were higher than the values cited by Rashad et al. [103], Li et al. [72] and Tang et al. [106]. Besides possessing many health benefits, the study discovered that the extract from pineapple waste contains polyphenols with antioxidant capacity to protect oil oxidation of emulsions in food, especially in the bakery industry [108].

6.1.4. Wine and Vinegar

High sugar content in pineapple waste, especially peels, makes them notable as a source for wine and vinegar production. Therefore, it increases the possibilities of utilising pineapple waste for alcohol and acetic acid to produce vinegar [10]. Beverages such as wine and beer can be made through the alcohol fermentation process and require an additional step such as oxidation to produce vinegar [17]. Production of vinegar from pineapple peel using three different acetic acid bacteria strains showed that optimum acetic acid yield (6.15 g/L) was found at 72 h fermentation time using propionic bacterium *acidipropionici* acetic acid bacterial strain. Umaru et al. [18] used the juice from pineapple waste to produce wine with 10.8% alcohol content by *Saccharomyces cerevisiae*. Then, it underwent oxidation to acetic acid (vinegar) and contained a total acidity of 3%. In contrast, lower alcohol content (7%) was observed from wine prepared using pineapple's peels and core [109]. However, 5% acetic acid was obtained despite the low alcohol content, which is higher in the previous study. The difference was due to the different fermentation methods used by the authors.

Correspondingly, there is lower alcohol content in wine produced from pineapple wine produced by *Saccharomyces cerevisiae* (6.60%) and *Saccharomyces bayanus* (6.75%) [110] compared to the alcohol content in [18]. In another research, Roda et al. [17] reported that physical and enzymatic combination before alcohol fermentation were required to produce good quality wines. By varying the *Saccharomyces cerevisiae* strain and temperature, a substantial difference in the wine's fruity character was detected. Other than that, the sensory evaluation of pineapple organic side-stream syrup revealed its potential when

combined in bakery products [111]. Although these studies proved that pineapple residues could be utilised as food enhancers and beverages, further studies should explore more the pineapple residue's utilisation potential in the food and beverage industries, in terms of its production by focusing on the quality and purity.

6.1.5. Organic Acid

Organic acid has broad applications in various industries, and over the years, there has been an upsurge in demand for organic acid, especially as additives and chemical feedstocks. Lactic, citric, formic and propanoic acids are common organic acids in the market as well as other types of organic acid [112]. Solid-state fermentation (SSF) is the most popular method used in producing organic acids other than chemical synthesis [113]. High sugar content and readily fermentable sugar in pineapple waste make it a suitable substrate for organic acid production. Table 2 shows several studies related to the utilisation of pineapple waste for the production of organic acids. Zain et al. [16] optimised the specific parameters for SSF of pineapple waste to produce lactic acid which resulted in a maximum lactic acid concentration of 103.69 mg/g (dry basis). However, a similar study by Aziman et al. [114] only managed to produce 0.0236 g/g of lactic acid using the same bacteria (*Rhizopus oryzae*). The difference between the results is due to the optimisation of the process parameters used by the authors. Zain et al. [16] investigated the optimal moisture content, incubation time, temperature, pH and inoculum size using central composite design (CCD) after the screening step using Two-level Factorial Design (2LFD) whereas Aziman et al. [114] only investigated the optimal particle size, moisture content, temperature, pH and inoculum size using 2LFD. Additionally, lactic acid produced using pineapple cannery wastes and *Lactobacillus delbrueckii* has a yield of about 79%. However, higher yields were obtained by Bustamante et al. [115], lactic acid production from orange peel yielding about 84% of lactic acid. However, lactic acid production by *Lactobacillus plantarum* using mango, banana and orange peels yielded 23.85%, 26.7% and 18.9% of lactic acid, respectively [116] which is lower than 79% lactic acid produced using pineapple waste by Aziman et al. [114]. Other than lactic acid, pineapple residues have also been converted to succinic acid. The outcome of the fermentation of liquid pineapple waste showed that the production of succinic acid by using pineapple liquid waste yielded nearly the same as using other carbon feedstocks [117]. In addition, citric acid was also produced from pineapple waste. The SSF of pineapple peel waste by *Aspergillus niger* has been evaluated by Ayeni et al. [118] and Kareem et al. [119], and it resulted in the production of 15.51 g/L and 60.61 g/kg citric acid, respectively. Previously, Imandi et al. [120] reported a higher amount of citric acid production from pineapple waste by SSF. Considering the broad application of organic acid in various industries, especially in food and pharmaceuticals, intensive research should explore pineapple waste utilisation to produce organic acid that is able to meet the market standard, so that the organic acids produced can be marketed in an industrial scale.

Table 2. Organic acid production from pineapple wastes.

Type of Organic Acid	Microorganism	Type of Pineapple Waste	Maximum Acid Production	References
Lactic Acid	<i>Rhizopus oryzae</i>	Solid	103.69 mg/g	[16]
Lactic Acid	<i>Rhizopus oryzae</i>	Solid	0.0236 g/g	[113]
Succinic Acid	<i>Escherichia coli</i>	Liquid	6.26 g/L	[116]
Citric Acid	<i>Aspergillus niger</i>	Solid (peels)	15.51 g/L	[117]
Citric Acid	<i>Aspergillus niger</i>	Solid (peels)	60.61 g/kg	[118]
Citric Acid	<i>Yarrowia lipolytica</i>	Solid	202.35 g/kg	[119]
Lactic Acid	<i>Lactobacillus delbrueckii</i>	Liquid	54.97 g/L	[121]

6.2. Bio-Packaging

Environmental problems associated with non-biodegradable materials' disposal have increased the interest in developing an environmentally friendly, biodegradable and edible materials. Polysaccharides and protein are the most common ingredients used to produce biodegradable materials. To improve their properties, cross-linker, plasticiser and antimicrobial agents were added as additives [14]. Pineapple waste is rich in cellulose, lignin, pectin and their derivatives, which makes it a suitable biodegradable packaging element [63]. Several studies have reported pineapple waste as potential substrate to be incorporated in making edible and biodegradable packaging. Rodsamran and Sothornvit [122] evaluated the use of pineapple peel as a natural plasticiser for the production of edible film. Increasing the pineapple peel extracts increased the total phenolic content; thus, it proved that besides its potential as a natural plasticiser, pineapple peels give good antioxidant properties to the film. Recently, extracted pectin from pineapple was cross-linked with citric acid or tartaric acid to produce an edible film [14]. The results showed improvement in film tensile strength as well as comparable chemical resistivity and thermal properties. The use of pineapple peel extract as the natural antioxidant agent was implemented to produce polyvinyl alcohol-starch films [123]. There are enhancements in the thermal and antioxidant properties of the produced films with pineapple peel extract. Furthermore, cellulose extracted from pineapple leaves by surface modification using silane coupling agent was used as filler in Polylactic Acid (PLA) [124]. Performance of PLA produced improved and showed high tensile strength value compared to pure PLA. However tensile strength of PLA added with jackfruit skin powder showed better tensile strength (53.2 MPa) [125] than PLA from pineapple waste (21.75 MPa) [124].

The fermentation of waste by selective bacteria produced bioplastics commonly called polyhydroxyalkanoates (PHAs). PHAs are bio-based plastics and are biodegradable. Few studies have reported the potential use of pineapple waste in producing PHAs. Earlier, Suwannasing et al. [15] reported that pineapple cannery wastes were used to produce PHAs. The produced PHAs were analysed using Fourier Transform Infra-Red (FTIR), and the results showed that the PHAs were present in the form of polyhydroxybutyrate (PHB). Other than that, the characterisation of PHA produced from pineapple peel waste using *Ralstonia eutropha* also showed PHB group characteristics, with two monomers with 4 and 8 carbons [126]. According to Sukruansuwan and Napathorn [127], canned pineapple industry waste can be utilised for PHB production by *Cupriavidus necator* strain A-04 without the need for a pretreatment. These studies showed that pineapple residues have great potential as a substrate for the production of green packaging. More studies should be conducted to improve the quality of the produced materials.

6.3. Bio-Adsorbent

To date, owing to its lignocellulosic content, agricultural waste has been acknowledged as an adsorbents' source for removing dyes and heavy metals from wastewater. Activated carbon is commonly used as a bio-adsorbent, and pineapple waste could be used as a substrate to produce activated carbon [128]. Over the years, pineapple waste has gained attention as a potential source for making bio-adsorbent with various studies being conducted and reported, as shown in Table 3. Selvanathan et al. [129] have investigated the removal of methylene blue dye using activated carbon derived from pineapple waste. The authors stated that a large amount of hydroxyl and carbonyl groups present in activated carbon from the pineapple crown contribute to the maximum adsorption compared to the peel and core. Mahamad et al. [130] also utilised pineapple waste for activated carbon in methylene blue removal. The maximum dye removal capacity of 288.34 mg/mg was achieved at 1:1 ratio of pineapple to zinc chloride, contributing to a high surface area of 914.67 m²/g. The methylene blue removal in this study was higher than dragon fruit peel bio-adsorbent which can only remove up to 192.31 mg/g of methylene blue [131]. In a recent study, Abd Latif et al. [132] reported that activated carbon from pineapple leaves resulted in 50 mg/g adsorption capacity of reactive black 5. Dye removal ranging from 7 to

100% was also reported when varying the impregnation ratio, carbonization temperature and time during activated carbon preparation. Bio-adsorbent prepared from pineapple leaf fibre immobilized with Zinc Oxide photocatalyst reached up to 95% removal efficiency in removing Congo red [133]. According to the authors, the produced bio-adsorbent can be used up to 3 times by maintaining more than 84% Congo red removal efficiencies, while activated carbon and biochar derived from pineapple waste for methylene blue removal showed that activated carbon impregnated with zinc chloride has higher adsorption capacity than biochar due to increased surface area and lower ash content [134]. Patel et al. [135] studied the performance of activated carbon derived from pineapple waste and Soapnut shell. The authors observed 96% of methylene blue removal from pineapple waste activated carbon compared to 99% from Soapnut shell. The lower adsorbent dose required to remove the methylene blue and higher surface area makes the adsorption capacity of the Soapnut shell better than that of pineapple waste-derived activated carbon.

Table 3. Various studies conducted related to the removal of various dyes using pineapple wastes.

Adsorbent	Dye	Removal Efficiency (%)	Adsorption Capacity (mg/g)	Isothermal Model	Kinetic Model	References
Hydrogel from pineapple peel cellulose	Methylene blue	ns	138.25	ns	Pseudo-second-order	[19]
Activated carbon from pineapple wastes	Methylene blue	38.6	ns	ns	ns	[128]
Activated carbon from pineapple wastes	Malachite green	18.7	ns	ns	ns	[128]
Activated carbon from pineapple wastes	Methylene blue	ns	288.34	Langmuir	ns	[129]
Activated carbon from pineapple leaves	Reactive black 5	ns	50	ns	ns	[131]
Pineapple leaf fibre adsorbents	Congo red	>95	ns	ns	ns	[132]
Activated carbon from pineapple waste	Methylene blue	96	ns	Langmuir	ns	[134]
Hydrogel from pineapple peel cellulose	Methylene blue	ns	153.85	ns	Pseudo second-order	[135]
Hydrogel from pineapple peel cellulose	Methylene blue	ns	101.94	Langmuir	Pseudo second-order	[136]
Hydrogel from pineapple peels	Congo red	ns	138.89	Langmuir	Pseudo second-order	[137]
Silver nanoparticles from pineapple peels waste	Methylene blue	98.04	ns	First-order kinetic model	ns	[138]
Pineapple peels	Safranin-O	ns	21.7	Freundlich	ns	[139]

Note: ns—not stated.

The hydrogels prepared from pineapple peel cellulose (PPC) reached the optimal adsorption capacity when 10% of kaolin was added [136]. Moreover, the thermal stability of hydrogels was upgraded, which affected the swelling ratio and pH when kaolin was added. Dai and Huang [19] conducted a similar study where the adsorption capacity increased to 138.25 mg/g when 10% of sepia ink was added. Recently, Dai et al. [137] evaluated the fabricated PPC hydrogels embedded with magnetic diatomite for the re-

removal of methylene blue that resulted in achieving 101.94 mg/g of adsorption capacity. Hydrogel from pineapple peels was also employed in the congo red adsorption, in which Dai et al. [138] prepared four different types of hydrogels. The highest congo red removal was obtained from the most lignin removed from the pineapple peel (BT-PP), and the adsorption kinetics followed a pseudo model of the second order; it was also found that the equilibrium data are a better fit with the Langmuir model. Silver nanoparticles from pineapple peel waste were able to remove about 98.04% of methylene blue according to Agnihotri et al. [139]. Other types of dyes such as methyl violet, safranin-O and malachite green have also been reported to be removed by pineapple-based adsorbent [74,129,140]. Other than dyes, biochar developed from pineapple peel was also synthesised to remove oxytetracycline, which is considered as possibly risky and poisonous to the well-being and safety of both humans and aquatic ecosystems [141].

Chromium, aluminium, lead and cadmium are some of the heavy metals that have been adsorbed by pineapple-based adsorbent. A compound such as chromium is carcinogenic and mutagenic when released into the environment. In order to remove chromium, the authors have reported that the effect of pH, bio-adsorbent dosage and temperature affected the dye sorption process, where the maximum adsorption capacities of pineapple possessed the highest value compared to lime [142]. Chromium removal by pineapple leaf fibre by polyethyleneimine-grafting had the highest adsorption capacity (222 mg/g) [143] compared to bio-adsorbent from date palm empty fruit bunch [144] and jackfruit peel [145] that reported lower chromium adsorption capacity of 70.49 mg/g and 13.50 mg/g, respectively. Remarkably, eliminating chromium ion from water bodies could be obtained from pineapple crown leaves, with the advantage of being a good and cheap alternative that does not require significant capital investment [146]. The removals of cadmium and lead were also studied by Ahmad et al. [147] and Mopoung and Kengkhetkit [148]. More than 90% removal efficiency was achieved with about 20–45 mg/g adsorption capacity. Similarly, removal of lead using plantain peels adsorbent observed more than 90% removal efficiency [149]. In this regard, intensive studies should be explored to assess pineapple-based adsorbent usage to remove hazardous pollutants, dyes and heavy metal from water bodies.

6.4. Bioenergy

This section highlighted the production of bioenergy from pineapple waste. The conversion of bio-based waste to bioenergy is considered as one of the practical approaches to producing renewable energy. Bioenergy can be divided into biofuel (bioethanol, biobutanol and biodiesel) and bioenergy (biomethane and biohydrogen).

6.4.1. Biofuel

There are emerging interests in the replacement of non-renewable fuel sources by biofuels. Compared to fossil fuels, biofuels are renewable, release fewer dangerous compounds during burning, reduce carbon dioxide emissions and absorb the most emitted carbon dioxide [150]. Table 4 shows the biofuel categories based on the feedstock sources. An example of a type of biofuel is bioalcohol, which can be produced through biological processes and is in high demand as solvent and fuels [151].

Besides bioethanol, which is the most popular bioalcohol produced, there are also others including biobutanol, biopropanol and biomethanol [150]. According to Ayodele et al. [152], bioethanol can be produced from non-food lignocellulosic biomass. Alcohol produced from food crops contributes a risk to food safety. Besides bioethanol, biobutanol is useful to replace petrol and can be used without changing the ignition engine [153]. Other than being able to withstand a mixture of fuel with high water percentage, biobutanol has high energy density and low volatility compared to petroleum-based fuel [69]. Petroleum diesel could be substituted by biodiesel, a mono-alkyl ester of long-chain fatty acid produced from the transesterification or esterification process [154]. Biodiesel is comparable with conventional biodiesel; it could reduce pollution, and it is renewable, harmless, biodegradable and has a high flashpoint [155]. Few studies have been conducted

in regard to producing biofuel such as bioethanol, biobutanol and biodiesel from pineapple waste biomass and will be further explained in Sections 6.4.1.1 to 6.4.1.3.

Table 4. Biofuel categories based on feedstock sources (adapted and modified from Lin and Lu [69]).

Generation	First	Second	Third
Examples of feedstock	Human food-based feedstock	Lignocellulose materials and other non-edible lipids, oils, solid municipal waste etc.	Microbial organisms
Production methods	Transesterification or fermentation reaction	Thermochemical or biochemical conversion processes	Lipid extraction or direct fermentation, transesterification, product purification
Product types	Biodiesel, bioethanol	Syngas, biodiesel, jet fuel, bioalcohol, pyrolysis liquid, etc.	Biodiesel, bioethanol, biobutanol, biogasoline, biohydrogen, biomethane, etc.
Representative feedstock	Canola, coconut, corn, cottonseed, hazelnut, olive, palm, peanut, rapeseed, rice, bran, soya bean, sunflower, etc.	Lignocellulosic waste, jatropha, rice or wheat straw, wood chips, paper pulp, etc.	<i>Chlorophyceae</i> , <i>Bacillariophyceae</i> , <i>Rhodophyceae</i> , <i>Bacillus licheniformis</i> , <i>Escherichia coli</i> , <i>Pseudomonas</i> sp., <i>Brevundimonas</i> sp., <i>Pelagibaca bermudensis</i> , etc.

6.4.1.1. Bioethanol

Bioethanol produced from food-based feedstock is known as the first-generation bioethanol. However, sustainability issues are associated with the first generation of bioethanol, such as food security, high cost and land usage [152]. Consequently, the first generation's limitation stimulated the second-generation bioethanol that mainly uses agricultural by-products and wastes as the primary feedstock. Pineapple waste's lignocellulosic composition has been seen as a potential feedstock for bioethanol production. Four steps are involved during the second generation of bioethanol: pre-treatment, hydrolysis, fermentation and biofuel upgrading [156]. Several popular techniques used in producing bioethanol are simultaneous saccharification and fermentation (SSF), pre-hydrolysis simultaneous saccharification and fermentation (PSSF), simultaneous saccharification and co-fermentation (SSCF), and consolidated bioprocessing (CBP) [157]. Table 5 shows several studies that have been conducted in producing bioethanol from pineapple waste. Earlier, Choonut et al. [158] produced bioethanol from pineapple peel waste and obtained about 9.69 g/L of bioethanol.

Later, a comparison of bioethanol production from pineapple juice, coconut milk and tuna juice was conducted and among the three feedstocks, and pineapple juice showed the highest bioethanol concentration of 22% *v/v* (dry basis) [159]. A higher yield of 23.6% was obtained using kitchen fruit waste [160]. Teoh and Hanani [161] produced 0.27 g/L of ethanol from pineapple waste through the SSCF technique. However, the bioethanol yield from pineapple was slightly lower than that of banana due to its complex structure. In another study, pre-treatment was applied to pineapple waste prior to SSCF, and it yielded 9.73 g/L of bioethanol [162]. According to the authors, the pre-treatment combination enhanced the reducing sugar concentration for bioethanol production. Lower yields ranging from 3.5 to 4.6 g/L were observed in pretreated fruit wastes from Amazon fruit industry [163]. Mund et al. [164] observed high glucose conversion was found after 72 h of incubation after pretreatment and 212 L of ethanol yield produced from 1 ton of dry pineapple leaf.

Table 5. Summary of works of literature on bioethanol production from pineapple waste.

Source	Bacteria	Raw Material (w/v)	Yield	Fermentation Method	References
Sonicated pineapple peels	<i>Trichoderma harzianum</i>	5%	197.6 g/L	ns	[20]
Pineapple leaves	Cellulase-xylanase concoction and <i>Saccharomyces cerevisiae</i>	5–40%	7.12%	SSF	[155]
Pineapple peels	<i>Saccharomyces cerevisiae</i> and <i>Enterobacter aerogenes</i>	20%	9.69 g/L	SHF	[156]
Pineapple peels	<i>Trichoderma harzianum</i>	5%	5.98 g/L	SHF	[157]
Pineapple waste	<i>Aspergillus terreus</i> and <i>Kluyveromyces marxianus</i>	50%	0.27 g/L	SSCF	[158]

Notes: separate hydrolysis and fermentation (SHF), simultaneous saccharification and co-fermentation (SSCF), simultaneous saccharification and fermentation (SSF), not stated (ns).

Gil and Maupoey [97] reported on the use of the SSF technique to increase ethanol production from pineapple core and peels. Comparison between SSF, direct fermentation and saccharification and fermentation techniques revealed that higher ethanol production could be produced from the SSF technique amounting to 5.4% (v/v). This study agrees with Silva et al. [139]; the authors stated that using the SSF method could produce higher bioethanol yield (96.21%) from PALF compared to the SHF method. The SSF technique was previously used to produce bioethanol from pineapple leaf waste by Chintagunta et al. [157]. The work was carried out using the SSF technique and cellulolytic enzyme along with *Saccharomyces cerevisiae* that resulted in 7.12% (v/v) of ethanol produced. However, the complex structure of pineapple peels would slow down the hydrolysis process during the bioethanol production. To overcome this problem, Casabar et al. [20] used ultrasonic pre-treatment prior to the fermentation process. Sonicated pineapple peels produced 197.6 g/L of bioethanol using *Trichoderma harzianum* as the fermentation bacteria. In the previous experiment, Casabar et al. [165] produced 5.98 g/L of bioethanol using separate hydrolysis and fermentation (SHF) techniques with the application of alkaline pre-treatment using sodium hydroxide. They found that the sodium hydroxide pre-treatment was not efficient in producing bioethanol from pineapple peels. Recently Chen et al. [166] used anaerobic ethanol fermentation to produce bioethanol with pineapple leaves as raw materials. According to the authors, fermentation using *Kluyveromyces marxianus* managed to produce 2.1 tons of bioethanol. Additionally, they were able to produce sustainable quantities of bioethanol to replace approximately 8.51% of transportation fossil fuel consumption in Costa Rica.

6.4.1.2. Biobutanol

The production of bioethanol traditionally undergoes a process called Acetone–Butanol–Ethanol (ABE) fermentation. During this process, sugar is converted to butanol by *Clostridium* spp. [153]. Lignocellulosic biomass especially agricultural waste possesses high potential as biobutanol feedstock due to its composition. According to Khedkar et al. [22], pineapple waste contains cellulose, hemicellulose and lignin, making them valuable as biobutanol feedstock. Khedkar et al. [22] in their study applied drying treatment to pineapple waste prior to acid hydrolysis for ABE fermentation using *Clostridium acetobutylicum* B-527. According to the authors, 97 g/L of sugar were released during the detoxification process with a maximum of 5.23 g/L of ABE titred after the procedure. A different study applied phenol and sulfuric acid pre-treatment at 180 °C and achieved 357.25 g/L of fermentable sugar [167]. In this study, fermentation by *Clostridium acetobutylicum* NRRL B-527 produced 5.18 g/L of biobutanol. Another attempt at using pineapple waste as the carbon source to produce biobutanol was conducted by Sanguanchaipaiwong and Lek-

sawasdi [168], and using ABE fermentation by *Clostridium beijerinckii* resulted in 3.14 g/L of biobutanol being produced and at a yield of 0.08 g/g. This study showed that even without any pre-treatment to the pineapple waste, biobutanol could still be produced.

6.4.1.3. Biodiesel

Triglyceride-rich biomass is the typical feedstock for the production of biodiesel. The major component of biodiesel is fatty acid methyl esters (FAME) that are produced via transesterification. During the process, the ester bond between glycerol and fatty acid chain was hydrolysed followed by esterification [150,155]. The conversion of triglyceride to FAME requires the reaction with alcohol with the help of a catalyst to produce glycerin and FAME. An attempt to utilise pineapple waste to produce biodiesel was performed by Kanakdande et al. [21]. Due to the high sugar content such as fructose, sucrose and glucose in pineapple waste, the authors used pineapple waste as the carbon source for lipid extraction in producing biodiesel. The combination of pineapple waste as a carbon source, municipal wastewater and *Candida tropicalis* (MF510172) makes possible to extract 13 mL/L of lipids. The extracted lipid then undergoes transesterification to produce FAME or biodiesel. Earlier, pineapple peels and sugar cane bagasse were used as carbon feedstock to optimise microalgae's lipid accumulation [169] although the lipid yield from pineapple (0.93 g/L) was lower than that of sugar cane bagasse (1.24 g/L). In the most recent study, pineapple leaves were used as the catalyst for biodiesel synthesis [170]. The calcined pineapple leaves have high catalytic activity and require low transesterification activation energy.

6.4.2. Biogas

Methane-rich biogas is generated from various types of feedstocks, especially food waste. According to Aili Hamzah et al. [171], biogas consists of mainly 50–75% methane, 19–34% carbon dioxide and less than 1% biohydrogen through the anaerobic digestion process. Other than containing high moisture content and biodegradability, the composition of the waste such as carbohydrate, protein and lipid is an excellent potential substrate for biogas production. In addition, food waste also contains various trace elements and organic matter that promotes microbial growth [172,173]. Through the anaerobic digestion process, biogas is produced by the degradation of feedstock facilitated by a group of microorganisms through several reactions. The mechanism of anaerobic digestion involves step-by-step processes and happens via hydrolysis, acidogenesis, acetogenesis and methanogenesis [151]. While biologically produced hydrogen has higher energy content, their combustion in the presence of oxygen will produce only water which makes hydrogen a cleaner energy compared to hydrocarbon fuels [174]. Table 6 shows the recent conversion of pineapple waste into biomethane. Biohydrogen can be created through an anaerobic digestion process involving various types of microorganisms and enzymatic processes. Popular fermentation methods to produce biohydrogen are dark fermentation, photo fermentation and combined fermentation [12]. The produced biogas can be used as bioenergy to supply electricity or as cooking gas if it contains 50% to 70% methane [12]. However, using methane and hydrogen contributes to storage issues due to the reactivity of hydrogen and low flammability of methane [175]. Thus, biohythane (a mixture of biohydrogen and biomethane) is produced through two-phase anaerobic digestion [25,176]. Some literature focusing on utilising pineapple waste to produce biogas such as methane, hydrogen and biohythane is discussed in Sections 6.4.2.1 and 6.4.2.2

6.4.2.1. Biomethane

A two-stage anaerobic reactor system was recently implemented to produce biohydrogen and biomethane from pineapple peels; according to the authors, throughout the methanogenic phase a maximum methane yield of 174.6 mL CH₄/g COD with 66.1% methane content was produced [25]. On that note, biohythane consisted of biohydrogen and biomethane and was produced through the two-stage dark fermentation process. Another attempt at using two-stage reactors to produce biogas from the co-digestion of pineapple

waste mixture and swine manure was undertaken by [176]. According to the authors, the biogas obtained from the process contained 65% methane and when heat pre-treatment was applied to the swine manure prior to the process, methane content increased from 64.82% to 70.91%. In a similar study, co-digestion of lignocellulosic materials and animal manures offers a solution to balance the C/N ratio of feedstock for anaerobic digestion [177]. Methane contents from pineapple peel reported by Nguyen et al. [176] were higher than those of durian shell (42.10%) [178], mono digestion of food waste (35.1–61.2%) [179] and orange waste (69%) [180]. Low methane yield was often observed when fruit wastes were used as single feedstock.

A recent study investigated by Aili Hamzah et al. [171] evaluated the potential of co-digesting pineapple waste with cow dung to produce methane gas. The results revealed that the highest methane yield of 17.19 CH₄/g VS could be achieved at a 1:2 cow dung to pineapple ratio. It was proven that methane production improved when pineapple waste was subjected to the co-digestion [178]. In a study conducted by Azevedo et al. [26], co-digestion of pineapple peel and pig slurry was investigated. They reported that the co-digestion enhanced the synergetic effects between C/N ratio, methane production and process efficiency. They believed that the synergic result of these materials was responsible for the improvement of anaerobic digestion. Dahunsi [23] investigated the biogas production from alkaline and acid pre-treated pineapple peels found that the pre-treated pineapple peels contained more methane than the untreated pineapple. To improve the biogas yield by lignin reduction, pineapple peel pre-treated with alkaline hydrogen peroxide improved the biogas production by 67% higher than the samples without pre-treatment. However, Dahunsi et al. [181] reported that alkaline pretreatment using sodium hydroxide could increase the gas production of pineapple peels and poultry manure by 91% compared to acid pretreatment. Wichitsathian et al. [182] also reported that pineapple waste's specific gas production rate increased from 132.05 L/kg of VS to 866.75 L/kg of VS after pretreatment was applied. For instance, the study by Aworanti et al. [183] on the methane potential from the co-digestion of pineapple peels and manures and the optimisation of process parameters such as temperature, solid content and substrate to inoculum ratio discovered that by operating the co-digestion process at 55.2 °C, 6.25% solid content and 1:2 substrate to inoculum ratio could produce a high biogas yield with 71.10% methane content. In a different study, Aworanti et al. [184] investigated the influence of substrate to inoculum ratio, temperature and agitation speed on anaerobic digestion of pineapple wastes and manure. According to the study, applying agitation to the anaerobic digester improved the biogas yield, and the highest methane content was achieved at 30 rpm agitation speed. However, increasing the speed from 30 rpm to 70 rpm contributes to the declining trends in biogas yield. Adding the combination of pineapple waste and cow dung at a ratio of 2:4 into the anaerobic digester could only produce the highest methane at 70.5% [185]. Earlier, Deng et al. [186] used pineapple leaf residue for biogas production and had a yield of about 662.8 L with 63.2% methane content from the process. Other studies by Nga and Trang [58] attempted to use different *Methanobacterium* strains, and the three microorganism strains used produced 57.4%, 57.2% and 57.4% of methane, respectively. Kumar et al. [187] compared the methane production from pineapple waste with two inoculum sources: cow manure and novel microbial consortia. The study showed that novel microbial consortia proved to be the best inoculum for biogas production from pineapple leaves. In addition, co-digesting leaves and peels of pineapple with novel microbial consortia as inoculum produced 56.61% methane compared to 49.2% methane from cow manure.

Table 6. Previous research works on methane production from pineapple waste.

Pineapple Part	Co-Substrate	Operating Conditions	Pre-Treatment	Methane Content (%)	References
Pineapple peels	-	T = 37 °C; STD = VDI 4630	Hydrogen peroxide and sulfuric acid pre-treatment	70	[23]
Pineapple peels	-	T = 37 °C; pH = 7; Agitation = 150 rpm	No pre-treatment	66.10	[25]
Pineapple waste	-	T = 35–45 °C; pH = 7–7.5; C/N = 30	No pre-treatment	57.40	[58]
Pineapple waste	Swine manure	T = 37 °C; pH = 7; Agitation = continuous	Heat shock	65	[176]
Pineapple waste	Manures	T = 55.2 °C; SIR = 1:2; HRT = 8 days TS = 6.25% (opt)	No pre-treatment	71.10	[183]
Pineapple waste	Manures	T = 60 °C; SIR = 1:3 and 3:1; Agitation = 30 rpm (opt)	No pre-treatment	58	[184]
Pineapple waste	Cow dung	T = ambient; SIR = 1:2.4; VS ≤ 8%; HRT = 92, 73 and 67 days	No pre-treatment	70.50	[185]
Pineapple leaf residue	-	T = 35 °C (opt); pH = 7; TS = 20%; C/N = 25	No pre-treatment	63.20	[186]
Pineapple peels and leaves	Cow manure and novel microbial consortia	T = 37 °C; pH = 7	No pre-treatment	56.61	[187]

Notes: T = Temperature; TS = Total Solid; C/N = Carbon to Nitrogen Ratio; SIR = Substrate to Inoculum Ratio; HRT = Hydraulic Retention Time; STD = Standard; opt = optimal; VDI = Verein Deutscher Ingenieure standard; VS = Volatile Solid.

6.4.2.2. Biohydrogen

An attempt at using two-stage reactors to produce biohydrogen and biomethane assisted with heat pre-treatment from pineapple waste has been conducted [176]. According to the authors, at the optimal hydraulic retention time of four and half days from the hydrogen fermenter, maximum hydrogen was produced at the rate of 1488.62 mL/L/d. In a similar study conducted by Chu et al. [25], the authors observed a good performance of the two-stage reactor in producing hydrogen. A maximum of 599 mL/L_R-d of hydrogen was obtained at an optimal 4 h of hydraulic retention time. Biohydrogen produced from pineapple waste assisted with diluted acid pre-treatment at various substrate concentrations demonstrated that the highest biohydrogen produced was by using 26.4 g VS/L and 0.3 N sulfuric acid [24]. Abd Jalil et al. [188] investigated the biohydrogen production from pineapple waste with co-culture bacteria that was immobilised onto loofah sponge and activated carbon. The highest biohydrogen produced from the pineapple waste with activated carbon was 35.9 mmol/hr/L_{substrate}. However, in terms of performance, loofah sponge showed better uniformity. Additionally, Reungsang and Sreela-or [174] conducted a statistical experimental design to optimise substrate concentration, pH and iron (II) sulphate concentration in producing biohydrogen from pineapple waste extract by anaerobic mixed cultures. From this experiment, a maximum of 1.83 mol H₂/mol glucose yield was achieved with the difference of only 1.13% and 1.14% of the predicted and actual outputs. Choonut et al. [158] produced biohydrogen and ethanol using *Enterobacter aerogenes* TISTR 1468, and 1416 mL/L of hydrogen were produced after 12 h of fermentation.

7. Future Perspectives and Challenges

This article as well as several others explored the benefits of using pineapple waste for product recovery [6,10,62,63]. However, it is still necessary to improve these products from

pineapple waste and make proper use of them. Nevertheless, there are different kinds of challenges in utilising pineapple waste to generate valuable products, from its processing to its commercialisation at the industry level.

Production of CNC from pineapple waste for various applications has been increasing for several years. Purification of CNC is needed through the implementation of an additional treatment process to ensure its purity. The properties of CNC produced should be further evaluated and enhanced to ensure its marketability. The application of pre-treatment should be considered to increase CNC's mechanical, barrier and thermal stability. Other properties such as water sorption, hydrophilicity, durability, applicability and safety should be further assessed before scaling up to market standards.

In the production of bromelain from pineapples, a long separation process, instability of enzyme produces, and low recovery have been the major challenges for researchers. Thus, it would be beneficial to explore different purification techniques, separation, stabilisation and exploration of bromelain application recovered from pineapple waste for industrial applications. However, some purification, separation and stabilization of bromelain require high capital and complex procedures. A simple, efficient and economical approach should be explored to ensure its marketability. Enhancement of enzyme properties should be discovered, and the effectiveness of bromelain enzyme should be tested in various applications not limited to only on medical and food industry applications.

There is still limited information regarding the application of bioactive compounds isolated from pineapple waste and the production of wine and vinegar. Further exploration and evaluation of the bioactive compound's potential application are still needed to meet the market needs. It is more valuable to utilise pineapple waste for food-based applications instead of non-food products. The increase in the world population has also increased the food production demand. The competition between land and feed using food waste for food products seems to be the most cost-effective solution. Producing wine and vinegar to meet market standards requires a lot of research. It is important to assess the quality of wine and vinegar produced from pineapple waste in terms of consumer health, benefits and their potential to be commercialised on an industrial scale.

On the other hand, organic acid production from waste is widely implemented using pineapple waste as feedstock. Despite the success of recovering acid from pineapple waste, extensive research is still required on the selection of microorganisms used and the addition of suitable pre-treatment to enhance its production. However, the available studies on organic acid lack the quality assessment to meet the market's standards; thus, intensive research should be conducted.

Cellulose from pineapple has been used to produce bioplastic by the derivation of cellulose to carboxymethyl cellulose [63]. However, enhancements are needed to overcome low mechanical strengths, low solubility and low structure cohesion. Cross-linking, the addition of plasticiser, antimicrobial agent and antioxidant could improve the bioplastic properties. The edibility of bio-packaging could be seen as one way to create zero waste material. However, commercial application can be complex for edible packaging since certain criteria should be met. To ensure the practicability for commercial applications, these products should also be well designed, engineered and suitable for the most appropriate foods and their products. The information on the utilisation of pineapple to produce bioplastic is limited. Whereas, studies related to the comparative cost analysis, commercialisation potential, film properties and biodegradability to market plastic are very limited in the available literature, and that opens a future research scope.

The pineapple waste proved its strength in the removal of dyes and heavy metals in several studies. It is necessary to test the usage of pineapple-based bio-adsorbent in the textile industry's wastewater and other industries' wastewater to investigate its efficacy for mass production. Even though the complex preparation process has been the major limitation in producing bio-adsorbent, several processes such as modification, cross-linking and compounding are needed [138]. To date, the research using pineapple waste-based bio-adsorbent has been limited to removing dyes and heavy metals from an aqueous

medium. The potential of this bio-adsorbent should be evaluated at an industrial scale that contains a mixture of different dyes. Comparative cost analysis should be conducted to assess the feasibility and cost-effectiveness of the bio-adsorbent since limited information regarding this was cited in the literature.

As such, converting pineapple waste to produce renewable energy such as biofuel and biogas could reduce the dependency on non-renewable energy and is considered a sustainable energy source. Even though there are many attempts to utilise pineapple waste to produce biogas and biofuel, the production is still low and is unable to meet the market's demands. The main concern for bioenergy production from pineapple waste is the low productivity as well as its purity. The biofuel production undergoes biochemical reactions involving enzymatic hydrolysis, fermentation and product recovery and requires a distillation process for further purification. Due to its complex structure, converting pineapple waste to biofuels needs pre-treatment to assist with the enzymatic hydrolysis and fermentation in achieving fast and high productivity. Without pre-treatment, these reactions are time consuming. However, the pre-treatment and distillation processes require high capital costs. It will be advantageous to discover a feasible and low-cost pre-treatment and purification method to reduce the cost; therefore, high production could be achieved for commercialisation purposes.

Numerous studies have been conducted on using various wastes as feedstock to produce biogas. Hence there is a potential to produce biogases such as biohythane, biomethane and biohydrogen by fermentation using pineapple waste. Still, different types of challenges arise in producing biogas from pilot scale to the industry level. Producing methane-rich biogas requires certain parameters control such as organic loading rate, temperature, hydraulic retention time and pH. Operating these parameters at an optimal condition is necessary depending on the feedstock conditions, and it is important to analyse its characteristics since different feedstocks are dissimilar based on their nature and complexity. It is also notably important to ensure the microbe's stability and balancing the nutrient for a successful process. Slow hydrolysis and low biodegradability are often the major problems during the anaerobic digestion of pineapple waste due to the complexity of lignocellulosic biomass [171]. To eliminate the aforementioned problem, pre-treatment has frequently been applied prior to the fermentation process. However, it is also challenging to select appropriate pre-treatment methods because some pre-treatment that deals with chemicals would contribute to the release of harmful substances to the environment. The employment of solid waste conversion of energy and materials from waste would minimize environmental and economic impact and achieve the sustainable development goals by 2030. Good waste management practice can be the antidote to fulfil SDG since solid waste management is an interconnecting issue directly linked to 12 out of the 17 United Nations Sustainable Development Goals.

8. Conclusions

To sum up everything that has been stated so far, this review emphasised the global pineapple production, waste generation and current conversion of pineapple waste into valuable products. According to the world pineapple production data available, there are increasing demands for pineapple fruits and pineapple-based products. High waste production is the outcome of a surge in global pineapple production. It is also a contributor to the increase of waste at the landfill and to the release of greenhouse gases. Conversion of pineapple waste into valuable products could be seen as a life cycle assessment towards solid waste and would minimize environmental and economic impact to achieve SDG. This review showed pineapple waste's potential as raw material to produce valuable products using different available conversion technologies. There are also massive opportunities for their conversion to energy generation such as biofuels and biogas. Different pineapple waste parts' characteristics and composition make them a potential bromelain, bioactive compound and CNC feedstock. There is also intensive research on the potential of utilising pineapple waste as a bio-adsorbent for the removal of dyes and heavy metals. Moreover,

the high sugar content in pineapple pulp, peel and core waste together with pineapple juice waste could play a significant role as potential feedstocks for biofuels, particularly for the production of second-generation biofuels. However, researchers currently have a lot of limitations and challenges in producing the mentioned products mainly due to the composition that hinders the process. Therefore, additional procedures such as pre-treatment or purification should be implemented, but the selected method should depend on technical, cost and environmental concerns. Therefore, such an additional process should be implemented wisely through future research to ensure that the production of the valuable product will be able to achieve market standard and production.

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Abbreviations

ABE	Acetone–Butanol–Ethanol
BT-PP	Bleaching treatment pineapple peel
CCD	Central composite design
CDU	Casein Digestion Units
CNC	Cellulose nanocrystal
COD	Chemical oxygen demand
FAME	Fatty Acid Methyl Ester
FAO	Food and Agricultural Organization
FTIR	Fourier Transform Infra-Red
GHG	Greenhouse Gases
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PPC	Pineapple peel cellulose
PSSF	Pre-hydrolysis simultaneous saccharification and fermentation
SHF	separate hydrolysis and fermentation
SSF	Simultaneous saccharification fermentation
SSCF	Simultaneous saccharification and co-fermentation
TS	Total solid
VS	Volatile solid
2LFD	Two-level factorial design

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