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Microbial biotechnology approaches for conversion of pineapple waste in to emerging source of healthy food for sustainable environment

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ABSTRACT

One of the most significant and difficult jobs in food sustainability, is to make use of waste in the vegetable and fruit processing sectors. The discarded fruits along with their waste materials, is anticipated to have potential use for further industrial purposes via extraction of functional ingredients, extraction of bioactive components, fermentation. As a result of its abundant availability, simplicity and safe handling, and biodegradability, pineapple waste is now the subject of extensive research. It is regarded as a resource for economic development. This vast agro-industrial waste is being investigated as a low-cost raw material to produce a variety of high-value-added goods. Researchers have concentrated on the exploitation of pineapple waste, particularly for the extraction of prebiotic oligosaccharides as well as bromelain enzyme, and as a low-cost source of fibre, biogas, organic acids, phenolic antioxidants, and ethanol. Thus, this review emphasizes on pineapple waste valorisation approaches, extraction of bioactive and functional ingredients together with the advantages of pineapple waste to be used in many areas. From the socioeconomic perspective, pineapple waste can be a new raw material source to the industries and may potentially replace the current expensive and non-renewable sources. This review summarizes various approaches used for pineapple waste processing along with several important value-added products gained which could contribute towards healthy food and a sustainable environment.

1. Introduction

In addition to being one of the most popular fruits in the world, pineapple (*Ananas comosus*) is also one of the most widely consumed edible members of the Bromeliaceae family. Costa Rica, Brazil, Thailand, Philippines, China, and India are the world main producer (Maia et al., 2012). Brazil is the world's second-largest pineapple grower, with 2.69 million tonnes produced in 2016, trailing only Costa Rica, which produced 2.93 million tonnes in 2016. In 2016, it was anticipated that the worldwide pineapple output would be 25.80 million metric tonnes (Mt) from 1.04 million hectares (Mha) and continuously increase by the year. It is believed that the history of

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pineapple begins in the early 16th century as the Spaniards brought the fruit to the Philippines, Hawaii, and Guam (Arun et al., 2021; Leão et al., 2015). The fruit may be harvested at any time of year; however, the sweetness of the fruit differs according to the weather and other factors.

Pineapple plant is a herbaceous perennial monocotyledonous that requires about 200 days on average to produce fruit, propagated vegetative, and can reach the height from 1 to 1.2 m with a width between 0.8 and 1.5 m (Ávila et al., 2021; Leão et al., 2015). It is a perennial plant with fibrous, narrow, and spiny leaves. The pineapple plant has around 30 to 50 leaves, each of which weighs 35 g on average, resulting in approximately 1 to 1.5 kg of trash per plant after cultivation (Sibaly and Jeetah, 2017). The plant has a thick and short stem with a fibrous root that goes under the soil from 15 to 30 cm depth (Leão et al., 2015). For each pineapple fruit, no matter what size or form the outer shell is, it will always have the same number of hexagonal bits. Fig. 1 shows the whole part of the pineapple plant.

Pineapple juice and flesh are often used in cuisines in many places around the world. As per their respiratory activity as well as ethylene production patterns during ripening, fleshy fruits are often divided into two physiological groups: climacteric (with high respiratory activity) and non-climacteric (with low respiratory activity) (Awasthi et al., 2019; Paul et al., 2012). Pineapple attracts numerous attentions not only for its mouth-watering taste when eaten but also for its many therapeutic properties such as suppressing cough and cold symptoms (Cervo et al., 2014). The average fraction of chemical elementals found in pineapple fruit are 73.13% C, 24.17% O, 2.7–10% N, 0–10% Ca, 0.1–0.18% P, 0.06–0.11% Fe, 2.89% K, 0.33% Mg, 0–0.02% Cu and O/C ratio of 0.33% (Awasthi et al., 2020a; Dahunsi, 2019; Mansor et al., 2018). In mature fruit, pineapple may contain 14% of sugar, bromelain, malic acid, citric acid, vitamin A and B (Bogha et al., 2020; Rashad et al., 2015).

2. Pineapple waste

The term waste by definition means anything unused, unwanted or being excess. Pineapple cultivation creates around 315,000 tonnes of agro-industrial wastes from the food company or from goods that were lost in postharvest each year, which is a significant amount of trash (Vega-Castro et al., 2016). The solid waste generated during pineapple processing has been determined to be around 75% of the fruit in the form of crown end, core, peeled skin, and other parts. The amount of waste generated during pineapple processing ranges from 25 to 35% of the total weight of the fruit (Qu et al., 2021; Selani et al., 2014). Food processing of pineapple produced approximately 20–40% (w/w) waste in the core and peel form (Nga, 2015; Ravindran et al., 2021).

Regardless of the environmental load, pineapple waste was fortunately recognized as a possible valuable components source. Pineapple waste is a nutrient-dense raw material that is high in protein, phenolic compounds, minerals, pectin, vitamins, sugars, and insoluble fibres (Diaz-Vela et al., 2013; Reshmy et al., 2022a). Pineapple waste (peel and core) contains about 76% fibre, of which 0.8% is the soluble fraction and the remaining percentage is the insoluble component (Martínez et al., 2012). Pineapple peel is known as a low-cost feedstock thus appropriate to be utilized for value-added biochemical production. Pineapple peel waste contains 35–50% cellulose, 20–35% hemicellulose, and 5–30% lignin. On a wet basis, pineapple peel typically contains 80–90% (w/w) moisture by weight (Namsree et al., 2012). Table 1 summarizes the chemical compositions in pineapple waste.

Pineapple waste is recognized as a possible source of bromelain, as well as other cysteine proteases, which may be found in various pineapple parts (Vicente et al., 2016; Wainaina et al., 2020b). The leaves of the pineapple are rich in fibres which are being utilized to produce natural fibres. It is estimated by Leão et al. (Leão et al., 2015) that the production of pineapple fibres per hectare per year will yield around 15 tonnes of waste. The chemical compositions in pineapple leaves contain holocellulose (70–82%), lignin (5–12%) along ash (1.1%) (Asim et al.,

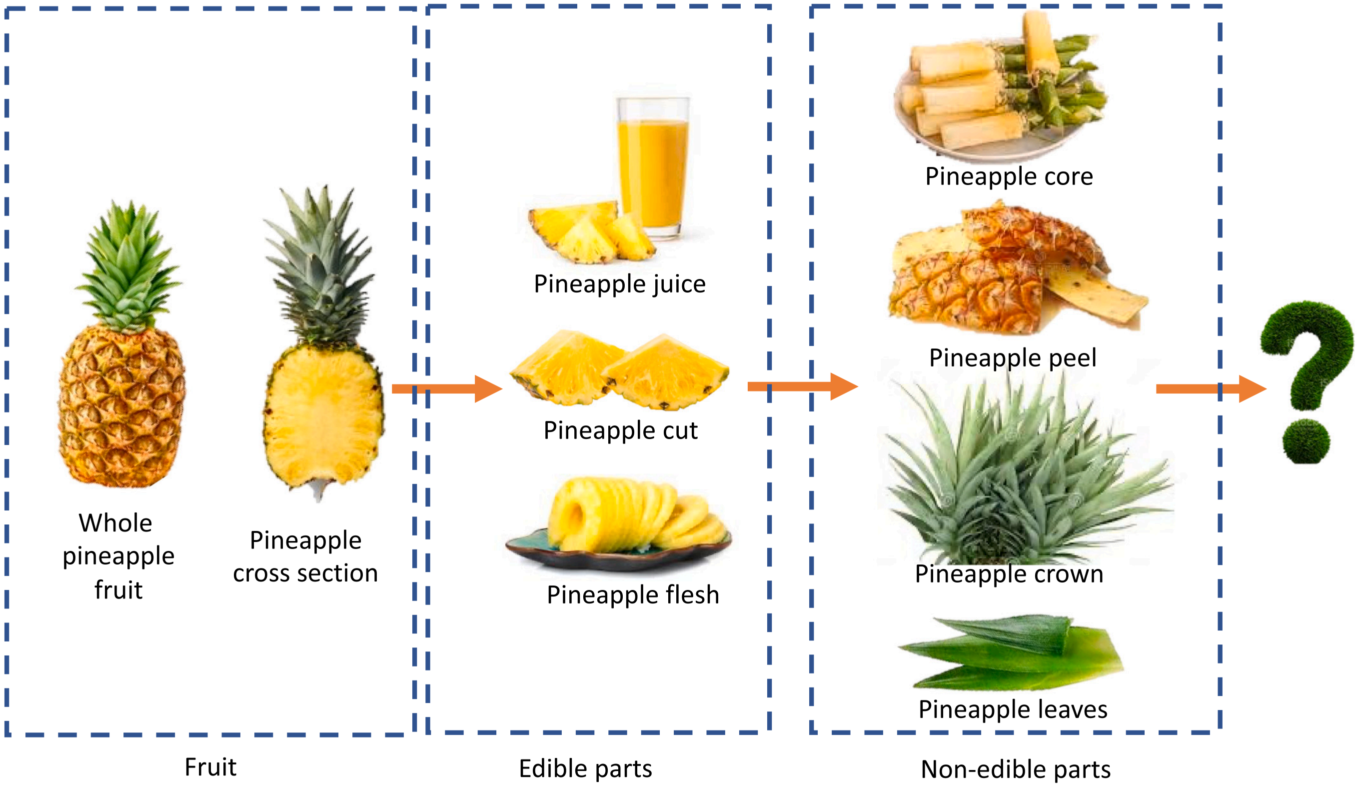

Fig. 1. Overall parts of the pineapple flesh and waste.

Table 1
Chemical composition of the different part of the pineapple waste.

Composition (%)	Peel	Core	Crown	Leaves	Root
Moisture	80–90[b]	–	–	81.6[j]	–
Ash	10.6[m]	–	0.40[i]	1.1–4.5[c,j,l]	0.86[l]
Organic carbon	–	–	–	43.43[g]	41.09[g]
Cellulose	35–50[b]	24.53[k]	29.6[i]	72.14[l]	–
Hemicellulose	20–35[b]	28.53[k]	23.3[i]	19.5–21.02[f,j]	17.96[l]
Holocellulose	–	–	–	70–85.7[c,j]	–
Reducing sugar	13.65[h]	–	–	–	–
Glucose	2.81[d]	2.56[d]	0.53[d]	–	–
Fructose	2.04[d]	2.24[d]	0.87[d]	–	–
Sucrose	–	–	–	–	–
Crude fibre	76[a]	76[a]	–	–	–
Crude protein	0.33[e]	–	4.2[i]	–	–
Total carbohydrates	17.53[h]	–	–	–	–
Total solids	7.8[b]	75[m]	75[m]	75[m]	75[l]
Lignin	5–30[b]	5.78[k]	4.5[i]	4.28–13.55[c,j,l]	13.22[l]
Volatile solids (%)	89.4[m]	–	–	–	–
Fat	0.46[e]	–	–	–	–

[a] Martínez et al., 2012.
[b] Namsree et al., 2012.
[c] Asim et al., 2015.
[d] Siti Roha et al., 2013.
[e] Khedkar et al., 2017.
[f] Banerjee et al., 2017.
[g] Mansor et al., 2018.
[h] Wijana et al., 1991.
[i] Ban-Koffi and Han, 1990.
[j] Daud et al., 2014.
[k] Pardo et al., 2014.
[l] Yves et al., 2018.
[m] Selani et al., 2014.

2015). Fig. 1 illustrates the parts of the pineapple fruits (flesh and wastes) while Fig. 2 shows from the linear to circular economic model aims at minimizing the waste and making the most of the resources. This regenerative method was in opposition to the typical linear economy, which is based on the trend paradigm of "take-make-dispose". Pineapple industrialization is one of the current practices that has been done as a circular economy strategy. The strategy can be divided into two groups (G1 and G2) depending on the type of pineapple processing applied.

Pineapple fruits that undergo simple processing treatments (peeling of the skin, removal of the crown and core) can be classified under G1. Basically, the G1 processing fruit is the one which produce ready-to-eat fruit as well as canned fruits, dehydrated fruits, and crystallized fruits. It will also undergo hard processing (trituration, pressing, etc.) to produce other form of ready-to-eat fruit such as pulps, puree, fruit and juice concentrates, pomace, and jams. From the G1 processing, mixture of by-products can be obtained contributing to the increase in total generated biomass. Meanwhile, the G2 processing is the fruits which undergo extraction processes to extract bromelain enzyme normally from the core and stem (Reshmy et al., 2021a; Wang et al., 2021). Two types of waste can be produced from the G1 processing which are press cake or secondary raw materials and remaining liquids that can be further valorised into flour production and for biofuels (Campos et al., 2020).

3. Approaches for pineapple waste valorisation

The food company produces a lot of trash, and it is becoming more and more prominent to recycle them (Oreopoulou and Russ, 2007; Yusree et al., 2022). This is partly due to innovations in process engineering as well as the by-products that arise from this process engineering. It is critical for governments to address the issue of waste repurposing to ensure long-term success (Roda et al., 2016). Agro-waste, such as pineapple waste as well as other agricultural waste, may be utilized as a substitute source for the synthesis of key chemicals such as sugars and enzymes since they are valuable raw materials that are also abundant sources of energy along with other nutrients (lipids, carbohydrates, proteins, lignocelluloses, etc.) which would be lost if they are discarded in the open dump yards and landfills (Kandaiah and Ramasamy, 2015; Xie et al., 2020). Researchers have concentrated their efforts on the exploitation of pineapple wastes as low-cost substrates for the manufacture of industrially relevant outcomes. Taking this into perspective, noble techniques are required to recover these added-value chemicals present in pineapple wastes, as well as to utilize pineapple wastes for other valuable tasks such as food processing (Fig. 3).

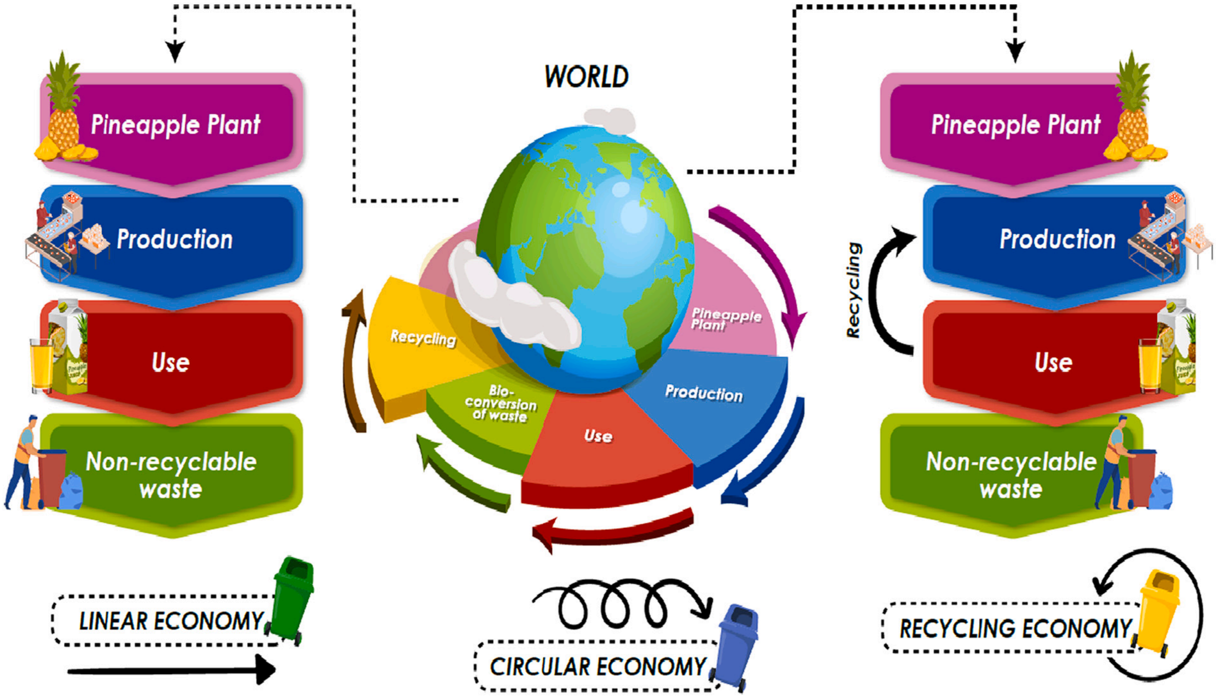

Fig. 2. From linear to circular economy for pineapple industrialization. Figure adapted and slightly modified from Campos et al. (Campos et al., 2020).

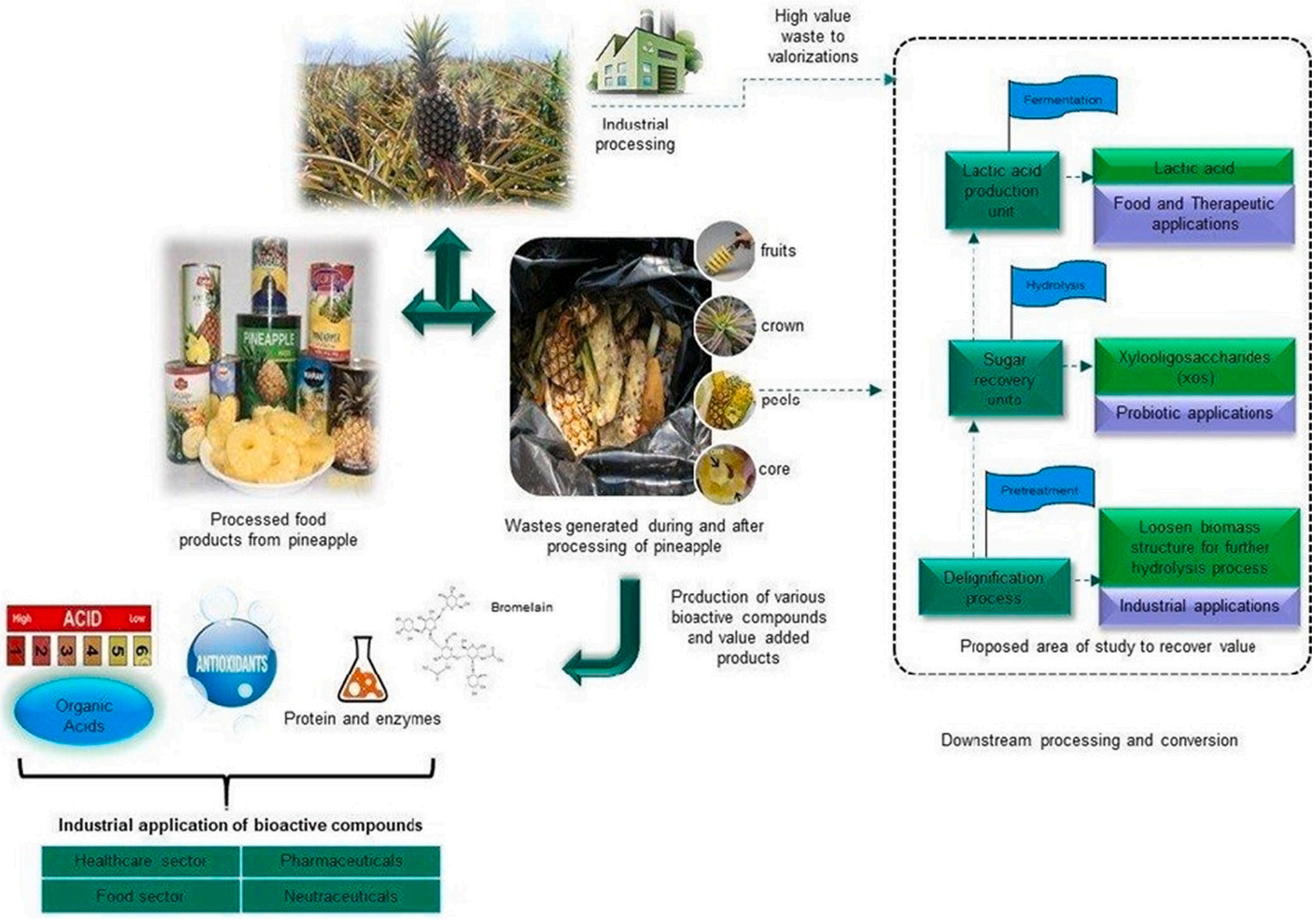

Fig. 3. Simplified graphical illustration of the process of transforming pineapple waste to value added product.

3.1. Pretreatment

Pretreatment is generally a process to reduce biomass recalcitrance by removing as much lignin from the biomass to ease the subsequent saccharification process especially when enzymes are used. Additional parameters that inhibit the action of enzymes include the crystallinity of cellulose, the degree of polymerization, the amount of moisture present, and the amount of accessible surface area. Several characteristics distinguish an efficient pretreatment from a less successful one. Reduced biomass particle size should be avoided to retain the pentose (hemicellulose) fractions, prevent the development of degradation products that impede the growth of fermentative microbes, decrease energy consumption, and keep prices low (Binod et al., 2012; Xu et al., 2021). There are many types of pretreatments performed on biomass such as by using chemicals, enzymes, mechanical, heat and various combinations thereof. Four different forms of pretreatments, HPC (high-pressure cooker), HPA (autoclave), boiling (B), and microwave (MW), were investigated and compared in terms of their efficacy (Roda et al., 2016). Pineapple peel and core made up most of the garbage. Experiments with pineapple waste exposed to microwave radiation (270 W) for intervals ranging from 5 to 20 min have shown a rise in the release of reducing sugar as the exposure time increases. In the presence of water, MW energy is equally absorbed by the solution. Due to the dielectrics characteristic of hemicelluloses, cellulose, water, along other molecular components, it can give rapid energy-efficient heating for biomass pretreatment (Ooshima et al., 1984; Reshmy et al., 2021b; Xu et al., 2020).

Furthermore, boiling pineapple waste could also be a viable pretreatment since it does not form inhibitors and enables for simple and cost-effective treatment of the cellulose substrate, which has the potential to rapidly release sugar into the hydrolysate (Laser et al., 2002). Pineapple waste is particularly sensitive to further breakdown because of the combination of high heat and pressure (HPA and HPC). Autoclave pretreatment has been proven to yield high sugar among the four pretreatments tested, either when conducted alone or when performed in combination with enzymatic saccharification (Roda et al., 2016). Khedkar et al. (Khedkar et al., 2018) investigated the influence of pretreatment enhancers, such as sulphuric acid, oxalic acid, phenol, and hydrogen peroxide on the solubilization of holocellulose from pineapple waste. To determine the greatest sugar release from these enhancers, they were tested alone and/or in combination with each other before entering the fermentation process to produce butanol. The findings from the study gave new insight into the augmentation of monomeric sugar release as well as the reduction of inhibitor production throughout the pretreatment period. Table 2 summarizes the recently published papers on pineapple waste valorisation techniques and their bioactive and functional compounds.

3.2. Saccharification

Saccharification is a process of breaking or hydrolysing complex carbohydrates into their monosaccharides component or simple sugars that are platform molecules for biofuel generation. For the production of bioethanol, the saccharification process is usually combined with fermentation. Usually, the saccharification process utilizes enzyme(s) as the catalyst to degrade the carbohydrate. It has been revealed that fresh pineapple peels along with the core may be used in enzymatic as well as

Table 2
Recently published papers on pineapple waste valorisation techniques and its bioactive and functional compounds according to food and non-food products.

Pineapple parts	Valorisation technique	Products	References
Food product			
Peels	–	Cereal bar	(Aparecida Damasceno et al., 2016)
Pineapple leaves	Drying	Dairy cow pellets	(Bogha et al., 2020)
Peels and core	Enzymatic hydrolysis	Sugars	(Conesa et al., 2016)
Pineapple-processing waste and pineapple on-farm waste, (e.g. peels, core and pomace)	Extraction, chemical/enzymatic hydrolysis, fermentation, dehydrogenation, decarboxylation	Food and therapeutic application	(Banerjee et al., 2017)
Peels, core	Pretreatment, saccharification, fermentation	Vinegar, wine	(Roda et al., 2016; Roda et al., 2017)
Non-food product			
Solid waste	Fermentation, saccharification, separation	Bioethanol/bromelain	(Gil and Maupoey, 2018)
Lignocellulose source	Microwave-pretreatment, saccharification, fermentation	Bioethanol	(Conesa et al., 2016; Tropea et al., 2014)
Extract of pineapple crude waste mixture	Enzymatic pretreatment, diafiltration	Bromelain	(Nor et al., 2016)
Peels		Fibre-rich pineapple peel powder	(Sah et al., 2016a)
Peels and core	Hydrolysis	Polyhydroxybutyrate	(Sukruansuwan and Napathorn, 2018)
Peels	Acid hydrolysis, detoxification, and fermentation process	Acetone-butanol-ethanol	(Khedkar et al., 2018)
Leaf	Saccharification and fermentation	Bioethanol and biomanure	(Chintagunta et al., 2017)
Leaf	Delignification and saccharification	Fermentable sugar	(Banerjee et al., 2017)
	Reverse micellar extraction	Bromelain	(Wang et al., 2016)
	Pretreatment	Ethanol and hydrogen	(Choonut et al., 2014)
Crown, core, leaves, stem, and peel	Adsorbent	Activated carbon	(Mahamad et al., 2015)
Leafs	Pulping, delignification	Paper	(Laftah and Wan Abdul Rahman, 2016; Sibaly and Jeetah, 2017)
Core, crown, and peels	Extraction	Bromelain	(Lakshminarasimaiah et al., 2014)
Stem and leaf	Slow pyrolysis	Pyroligneous acid	(Mathew et al., 2015)
Core and skin	Autohydrolysis	Bioactive compounds and glycoside	(Sepúlveda et al., 2018)
Crude waste mixture	Separation	Bromelain	(Nor et al., 2016)
Pulp, peels, and skin	Separation	Glucose	(Seker and Mohd Zain, 2014)
Stem, leaf, fruit	Adsorbent	Bioadsorbent	(Mopoung and Kengkhetkit, 2016)

fermentative procedures to produce cooking vinegar and wine with antioxidant characteristics (Awasthi et al., 2021a; Roda et al., 2017; Wainaina et al., 2020a). Banerjee et al. (2017) have also worked on saccharification and delignification of the pineapple leaf waste by utilizing cellulase-xylanase and laccase concoction, respectively. Enzymes known as cellulase, which are mostly exoglucanase and endoglucanase, are responsible for breaking down cellulose into its constituent parts, cellobiose and glucan oligomers, which are then broken down further by alpha-glucosidase to provide glucose monomers.

Furthermore, xylanase which is produced along with cellulase acts on the lignocellulose hemicellulose to release pentoses and hexoses thus increasing the reducing sugar yield. Laccase-mediated delignification prior to saccharification was reported to enhance the sugar yield via saccharification compared to saccharification alone (Awasthi et al., 2020b; Banerjee et al., 2017). Yu et al. (2014) previously found that pretreatment with laccase enhanced enzymatic hydrolysis efficiency, but only for furfural hydrolysate. Meanwhile, Gil and Maupoey (Gil and Maupoey, 2018) have performed two types of saccharification on blended pineapple solid waste which are CSF (consecutive saccharification and fermentation) and SSF (simultaneous saccharification and fermentation). The SSF was reported to enhance ethanol output by lowering inhibition of yeast activity caused by the excess of glucose through the gradual transformation of sugars into ethanol in the linked process of fermentation (Sanchez and Cardona, 2008). Hydrolysing enzymes, viz. cellulase and hemicellulases are usually added to degrade the long chain and complex carbohydrate into simpler units. Hence, efficient saccharification is required to obtain a good product yield in the fermentation process.

3.3. *Fermentation*

There have been many kinds of approaches used by researchers to valorise pineapple waste. Pineapple waste as complex carbohydrates including hemicellulose and cellulose is high in simple sugars which may be hydrolyzed to produce fermentable sugars (Gil and Maupoey, 2018). Sugars are usually fermented into alcohols using yeasts such as *Saccharomyces* sp., *Candida*, *Kloeckera*, *Hanseniaspora*, *Brettanomyces*, *Pichia*, *Lanchacea*, and *Kluyveromyces* are among the most studied non-Saccharomyces yeasts that have gained significant interest for use in fermentation (Lakshmi et al., 2021; Maicas, 2020). The utilization of pineapple wastes as a proteolytic enzymes source, on the other side, might be a promising option (Ketnawa et al., 2012).

Recent research by Kavuthodi and Sebastian (Kavuthodi and Sebastian, 2018) attempted to achieve the valorisation of pineapple waste for the cost-effective manufacture of the pectinolytic enzyme utilizing pineapple stem extract (PSE) medium to produce pectinolytic enzyme from pineapple waste. With the help of *Bacillus subtilis* BKDS1, Kavuthodi and Sebastian have concentrated on the synthesis of pectinase as an added value product from the primary agro-waste pineapple stem. Pectinolytic enzymes are extremely important in today's biotechnology era, with their wide-ranging uses primarily in the textile and food industries, as well as in other industries. Hansen et al. (Hansen et al., 2015) have noted that the utilization of SmF (submerged fermentation) is technically easier as compared to SSF (solid-state fermentation). SmF is typically used in the manufacture of enzymes by bacteria due to the demand for a larger water potential (Kamal et al., 2017; Lun et al., 2014). While the SSF has a few advantages over SmF, the most significant benefit of SSF is that it has lower capital and operational expenses since it uses low-cost agro-industrial and agricultural wastes as substrates (Mussatto et al., 2012). Consequently, the disadvantage of SmF can be minimized by the development of low-cost media comprised of agricultural leftovers, such as those utilized by horticulturalists (Kavuthodi and Sebastian, 2018).

3.4. *Autohydrolysis*

To recover bioactive chemicals from agro-industrial wastes, a variety of extraction techniques have been developed and tested (Liu et al., 2021b; Santana-Méridas et al., 2012). The autohydrolysis process (also called aqueous processing or liquid hot water) is one of the alternative technologies for extraction, which utilizes water as the sole extraction medium or solvent. Sepúlveda et al. (Sepúlveda et al., 2018) have opted for the autohydrolysis process and assessed for the polyphenols and glycosides extraction from pineapple waste. Several benefits of autohydrolysis include the absence of chemical solvent, the absence of corrosion issues, the simplicity of operation, the cost-effectiveness, and the economy of the system (Ruiz et al., 2013). Both temperature and time were significant parameters to extract glycosides (glucose and fructose) while the temperature is the most influenced variable for the release of antioxidants during the autohydrolysis (Sepúlveda et al., 2018).

Steam explosion is another type of autohydrolysis that is gaining interest. Some reports have mentioned combinations of other chemicals (acid or alkali) in steam explosion reactors to enhance cellulose or hemicellulose extraction from the biomass (McIntosh et al., 2016; Narisetty et al., 2021). Another group of researchers concluded that this procedure is an environmentally safe and efficient method of extracting antioxidant phenolic chemicals (Ballesteros et al., 2017; Madhavan et al., 2021b). Autohydrolysis is regarded as a viable option for the sustainable extraction process in the pursuit of high-value-added molecules (bioactive chemicals and glycosides) for future usage in health, cosmetic, food, and industrial applications.

3.5. *Other extraction methods*

The enzymes generated from pineapple waste are among the high-value substances found in pineapple waste that promises several industrial applications. Among the enzymes successfully produced from pineapple waste includes bromelain, pectinase, xylanase and cellulase (Abu Yazid and Razanah Roslan, 2020; Ridzuan et al., 2020; Saravanan et al., 2013). Guo et al. (Guo et al., 2018) have used reverse micelles from Gemini surfactants, pentamethylene-α,ω-bis (dodecyldimethyl ammonium bromide), dodecamethylene-α,ω-bis(dodecyldimethylammonium bromide), pentamethylene-α,ω-bis(cetyl-dimethylammonium bromide) and octamethylene-α, ω-bis(cetyldimethylammonium bromide) to extract bromelain from pineapple peel. Ever since bromelain was successfully used in several industrial applications, there has been an increased interest in its extraction and purification. To summarize, reverse micelles are aggregation of surfactant molecules that are disseminated in a continuous organic solvent medium and have an inner core of water molecules (Liang et al., 2011; Wang et al., 2016).

Protein transfer between the aqueous and reverse micellar phases is mostly governed by electrostatic interactions between protein and surfactant, with the target protein being thought to be smaller than the reverse micelle water core (Hebbar et al., 2012; Madhavan et al., 2021a). Using this new purification method, no natural function or activity is lost throughout the process, the system is simple to scale up and can operate continuously (de Lencastre Novaes et al., 2016). The use of reverse micelle extraction in conjunction with ultrafiltration may be able to improve the purification of bromelain (Hebbar et al., 2012; Madhavan et al., 2022). In contrast, the fundamental drawback of reverse micelle extraction is that the protein must be unfolded or denatured before it can be effectively extracted from the biological system (Guo et al., 2018; Wainaina et al., 2019).

3.6. *Separation technique*

After pineapple waste has undergone the above-mentioned processes, a separation technique is often required. Rojas et al. (Rojas et al., 2018) have used ammonium sulphate (AS) to precipitate endopeptidases extracted from pineapple waste and separated them from its buffer solution. Because of its solubility, AS is one of the most often utilized salts for precipitating proteins (Duong-Ly and Gabelli, 2014; Wang et al., 2013). Adding salt causes the protein to lose water, allowing its hydrophobic areas to bind together intermolecularly. This precipitation mechanism is called salting out. Proteins with more hydrophobic surface areas agglomerate and precipitate more quickly than proteins with fewer hydrophobic surface regions (Duan et al., 2021; Rojas et al., 2018). Ultrafiltration and microfiltration which rely on membrane-based separation rather than on enzyme precipitation in organic solvents or salts are also being considered. Pressure-driven membrane technologies such as ultrafiltration and microfiltration are utilized for protein purification and separation (Awasthi et al., 2022c; Saxena et al., 2009).

Ultrafiltration membranes are made to retain proteins and other macromolecules, while microfiltration membranes are best suited for the separation of tiny particles ranging from 0.1–10.0 m in diameter. It is possible to create a protein-rich stream that can be recycled as well as a medium appropriate for continued fermentation by using membrane separation methods to concentrate protein. Two-stage ceramic ultrafiltration has been used to separate bromelain from crude pineapple waste (Nor et al., 2016). The 75 kDa membrane was followed by a 10 kDa membrane in the two-stage ultrafiltration. A membrane with a pore size smaller than the protein's molecular size is used to capture and concentrate the permeate from the first ultrafiltration stage in the retentate. Due to their higher chemical, thermal, and mechanical qualities, ceramic membranes can be more durable and long-term options than polymeric ones. Ceramic membranes can also be cleaned under harsh circumstances (Duan et al., 2020; Lee et al., 2015). Using this technique, the bromelain was successfully purified up to 2.5-fold.

3.7. *Adsorbent*

Heavy metals, pesticides, and other pollutants are being released into the environment due to increased industrialization and human stress. In industrial applications, pineapple wastes have the potential to replace synthetic adsorbents like those now in use. Pineapple leaves have been used to synthesized activated carbon fibres (ACFs) activated with H_3PO_4 (Beltrame et al., 2018; Reshmy et al., 2022e). The ACFs are carbonaceous amorphous materials having high adsorption capacity and surface area, fast adsorption kinetics, functionalized surfaces, along uniform pores (Li et al., 2015; Reshmy et al., 2022d). To remove caffeine from water, the ACF has been used as an adsorbent material, and the adsorption process has been shown to be spontaneous. In water bodies, caffeine is a resilient molecule that indicates wastewater discharge (anthropogenic pollutant) and has claimed it as an emerging contaminant (Matamoros et al., 2016). Meanwhile, Gogoi et al. (Gogoi et al., 2018) have chemically modified the surface of pineapple crown leaf (PCL) for the adsorption of Cr(VI) and Cr(III) ions from aqueous solution. Hydrogen peroxide and acetic acid were used to add a few $-OH$ groups to the PCL surfaces.

An unsaturated group such as alkene $-CH_2{=}CH_2-$ present on pineapple leaves can adsorb metal ions through weak interactions (Ponou et al., 2011). As a result, the weak olefinic bond was chemically modified to hydroxyl groups to produce stronger connections with chromium ions. As a carcinogenic and mitogenic element, chromium is widely distributed in the Earth's crust (Ponou et al., 2011). Cr(VI) and Cr (III) are the types of chromium that are found in the produced wastes, with Cr(VI) having a greater transmission rate and being more harmful to people (Chen et al., 2011). Moreover, biochar was examined as a possible adsorbent for the treatment of contaminants in wastewater. As a result, a number of $La(OH)_3$-modified magnetic pineapple biochar were created and employed as phosphate adsorbents (Awasthi et al., 2021b; (Gaur et al., 2020; Liao et al., 2018)). The development of aquatic species requires phosphate, yet excessive phosphate emissions to the runoff system are known to induce eutrophication, which leads to a decline in water quality, the collapse of aquatic ecosystems, and even algal bloom. As a result, it is critical that phosphate be removed from wastewater prior to its discharge into the environment.

Materials decorated with lanthanum oxides or hydroxides as well as magnetic media can increase adsorption effectiveness in phosphate removal while also making the materials easier to recover from water. Liao et al. (Liao et al., 2018) found that the phosphate adsorption capacity of pineapple biochar was 27 times greater than that of most adsorbents. It has also been found that pineapple waste may remove colour molecules from industrial wastewater (Harirchi et al., 2022; Leite et al., 2017). A bio-adsorbent that is suitable for separating undesired chemicals for a given purpose may be designed and developed with the help of extensive and innovative research. Bio-adsorption methods employing biowaste have added benefits over other processes because of the local availability, cost-effectiveness of resources, and decreased environmental consequences are available.

3.8. *Papermaking and activated carbon*

Pineapple leaf fibres can be used to make paper in the future instead of relying solely on hardwoods (Jose et al., 2022; Sibaly and Jeetah, 2017). In the worldwide pulp and paper industry, wood is the primary raw material, and this has led to the loss of forest resources, which has imparted a negative effect on the environment. Sibaly and Jeetah have also mixed the pineapple leaf fibres with cane-bagasse and wastepaper at different ratios and paper with the most abrasion-resistant and the most crease-resistant were determined. Tensile strength, thickness, absorbency, bursting strength, abrasion resistance, and crease recovery test have been conducted to develop quality papers. Moreover, pineapples grown via selective breeding have been shown to have a greater cellulose content than wood fibre, which suggests that non-timber fibre is possible to be a good alternative for papers (Aremu et al., 2015; Liu et al., 2021c). Consequently, any country that uses pineapple fibres for paper manufacture may profit substantially from the usage of natural fibres to increase their sustainability and economics while minimizing the amount of trash to be sent to the landfill.

On the contrary, Sodtipinta et al. (Sodtipinta et al., 2017) produced activated carbon from the hydrothermal process, chemical activation, and heat treatment in an argon environment using pineapple leaf fibres. Chemical activation using potassium hydroxide (KOH) was frequently employed to produce a highly porous carbon material network (Awasthi et al., 2022a; Liu et al., 2021a; Wang et al., 2013). The capacitive performance of carbon material testing has been improved due to the high degree of KOH activation which has increased the specific surface area of the carbon. Sustainable utilization of the by-products from the pineapple industry to produce high-value goods has given new life to the pineapple waste stream. All these investigations led to a more dependable and strategic approach to the management of pineapple wastes in order to maintain a cleaner environment which can boost the economic growth of a nation.

4. Extraction of bioactive and functional ingredients for food

4.1. *Antioxidant*

Research focusing on the potential application of natural antioxidant compounds in food, cosmetic, and pharmaceutical industries has gained considerable importance nowadays owing to the implication of the synthetic antioxidants compounds such as TBHQ (tert-butyl hydroquinone), PG(propyl gallate), BHT(butylated hydroxy toluene), and BHA (butylated hydroxy anisole) as promoters for carcinogenesis and as one of the causes of liver damage (Embuscado, 2015; Qin et al., 2021c). One of the most important categories of natural antioxidants of interest is of plant origin and belongs to the phenolic and polyphenolic class of compounds (Shahidi, 2015). Fruit processing byproducts, such as pineapple wastes, are formed in great amounts during industrial processing are found to be very rich in bioactive components and have the same antioxidant activity as the fruit pulp (Segovia Gómez and Almajano Pablos, 2016). These bioproducts can influence environmental pollution and thus need to be managed properly. Thus, instead of discarding these by-products as waste, they can be utilized as sources for bioactive compounds such as polyphenols and natural antioxidants (Ibrahim et al., 2017). Several studies have reported excellent findings of phenolic compounds from pineapple by-products. For example, the assessment of the flours prepared from pineapple fruit peels exhibited that this industrial waste has significant amounts of antioxidant activity (31.82 ± 1.36 μM Trolox g^{-1}) which is higher than those found in melon (Conesa et al., 2016; Sabino et al., 2015). Thus, the addition of pineapple fruit peels flour to other food items might enhance the nutritional quality of the product.

Besides, the antioxidant activity of pineapple peel extract was assessed utilizing radical scavenging of 2, 2-diphenyl-1-picrylhydrazyl (DPPH) activity along with ferric-reducing antioxidant power (Afsharnezhad et al., 2017; Awasthi et al., 2022c; Xie et al., 2006). The capacity of the extract to scavenge free radicals through the donation of hydrogen is what determines the antioxidant activity measured using the DPPH free radical. The ability of pineapple peel extracts to scavenge DPPH is lower (52.3%) compared to orange peels (256.7%), apple (178.9%), banana (109.3%) and kiwi (75.7%) based on the analysis. The FRAP test analysis also displayed that the reducing powers of pineapple peel extracts are lower compared to other peels extract. Further analysis showed that the radical scavenging activity of pineapple peels is due to the presence of total phenol, flavonoid, and anthocyanin. Similar results have been reported for the main polyphenolic constituents in pineapple peels by Li et al. (Li et al., 2014). The results of the study revealed that the main polyphenolic compounds in pineapple peels were 19.50 mg/100 g of ferulic acid, 31.76 mg/100 g of gallic acid, 50.00 mg/100 g of epicatechin along with 58.51 mg/100 g dry extracts of catechin. All polyphenolic compounds existing in pineapple peels demonstrated their antioxidant abilities with structure-activity relationships even though it is lower than other extracts studied.

Furthermore, the extraction of phenolic compound of pineapple peels using Microwave-Assisted Extraction (MAE) at 30 °C utilizing deionised water with a microwave power of 250 W displayed the best operating condition for the extraction process producing 206.46 mg GAE/g dry weight with 13.65 mg/mL DPPH value (Alias and Abbas, 2017; Choonut et al., 2014). In addition, the feasibility of pineapple waste as a substrate to produce phenolic compounds by *Kluyveromyces marxianus* NRRL Y-8281 was investigated (Rashad et al., 2015). Fermented pineapple waste (FPW) showed the highest levels of antioxidant activities compared to unfermented pineapple waste (UFPW). The results of in vitro anticancer activity in different human cell lines showed that the fermented extract was more compelling than the unfermented extract and can be used as a good candidate for novel therapeutic strategies for cancer.

Besides pineapple peels, the phenolic antioxidants contained in pineapple leaves have been discovered to be in greater concentrations. Thus, it is suggested that this plant waste is also beneficial to the food and healthcare industries. A previous study reported the potential of pineapple leaves for the treatment of hypolipidemic which is the main factor for cardiovascular disease development (Awasthi et al., 2022b; Xie et al., 2007). Investigation of ethanolic extract from pineapple leaves in mice showed the inhibition activity of 3-hydroxyl-methyl glutaryl coenzyme. A reductase can selectively stimulate the activity of plasma lipoprotein lipase by binding to the enzyme. In the experiment, it was discovered that pineapple leaves may have the same mechanism of action as statins but have different actions than fibrates. As a result, it was proposed that pineapple leaves could be used as an alternative source of fibrates, particularly in patients who are unable to tolerate the side effects of fibrates. The impact of ethanolic extract from pineapple leaves on diabetic-dyslipidemic rats was also studied where this plant extract demonstrates the anti-oxidative, anti-dyslipidemic along anti-diabetic activities that might be helpful for diabetes treatment as well as its complications and can be developed into a new potential natural medicinal product. Similarly, investigation towards the effects of this extract on insulin sensitivity in rats and HepG2 cells revealed that this ethanolic extract could be used to treat insulin resistance in diabetic patients because it could inhibit the development of insulin resistance in both high-fat diet-fed diabetic rats and diabetic rats treated with low-dose streptozotocin, as well as in HepG2 cells (Narisetty et al., 2022; Reshmy et al., 2022c; Xie et al., 2006).

4.2. Bromelain

The pineapple juice extraction process normally yields around 60% of waste. Due to the unsuitability of the pineapple solid wastes to be used as cattle feed or utilization as compost or as an organic fertilizer, value addition for this solid waste can be done by the extraction of proteolytic enzyme or so-called bromelain (Chintagunta et al., 2017; Lakshminarasimaiah et al., 2014). Pineapple waste including stem and peel could provide a valuable source of expensive bromelain extract. It is also found in cores and leaves. Bromelain has several industrial applications, mainly in food, medical, pharmaceutical, cosmetic and other industries as well (Ramli et al., 2017; Reshmy et al., 2022b). Since bromelain has been discovered to be a proteolytic enzyme candidate of significant biological and economic importance, massive progress was made for understanding its function as well as action (Qin et al., 2021b; Ramli et al., 2018). The bromelain plays an important role in the food industry which include improving flour and dough properties in the baking industry, aiding in the palatability of protein and muscle food by increasing tenderness, generating fish protein hydrolysate, as an anti-browning agent which constrains the browning process of fruits and phenol oxidation and enhances alcohol production process (Benucci et al., 2011; Elavarasan et al., 2014; Ketnawa and Rawdkuen, 2011; Seker and Mohd Zain, 2014; Sarkar et al., 2017). Meanwhile, in human health, bromelain is responsible particularly for inhibition of platelet aggregation, fibrinolysis, cancer treatment by modulation of tumour growth, enhancement of antibiotic effects, third-degree burns, mucolytic and gastrointestinal actions as well as a drug for the oral-systemic treatment of inflammatory (Amini et al., 2013; Chobotova et al., 2010; Qin et al., 2021a; Ramli et al., 2017).

Extraction of bromelain from solid pineapple waste has been reported by Lakshminarasimaiah et al. (Lakshminarasimaiah et al., 2014). In their research, protein content and enzyme activity in different parts of pineapple extracts were analysed where high content of bromelain was found in the crown part followed by peel and core. Investigation on bromelain extract of Thailand local pineapple cultivars wastes, Nang Lae and Phu Lae, demonstrates that both cultivars displayed maximum protein content and proteolytic activity from the crown, while the least amount was displayed from the stem (Ketnawa et al., 2012; Xie et al., 2007). Characterization analysis at different pH and temperatures of the extracts from the peel, core, and crown demonstrated the highest caseinolytic activity at pH 7.0, whereas stem extracts gave the highest activity at pH 8.0. The highest activity was obtained at 50 °C and 60 °C for both extracts from the Nang Lae and Phu Lae cultivars, respectively.

There have been several research conducted to study the efficacy of commercially extracted proteolytic enzymes such as bromelain from pineapple waste. For instance, successful bromelain separation from core and peel of pineapple was achieved using a membrane technology approach including microfiltration and ultrafiltration (Bardiya et al., 1996; Gil and Maupoey, 2018). Bioactive protein extraction was directly attained from the liquid stage without the addition of water or other solvents during the extraction process. The proteolytic activity of the lyophilised powder has been calculated to be between 340 and 805 Gelatine Digestion Units (GDU) at the end of the procedure, which is comparable to other commercial preparation processes. Another alternative approach for purification using conventional separation for bromelain extraction from pineapple waste is described by Wang et al. (Wang et al., 2016). Bromelain separation from pineapple peel was performed using reverse micelles extraction approach where gemini surfactant C_{12}-8-C_{12}.2Br (octame thylene-a,x-bis(dimethyl-dodecyl ammonium bromide)) demonstrates optimum protein recovery and purification fold of 163% and 3.3, respectively. Another method for producing active bromelain enzyme was using ammonium sulphate precipitation (40–80%) followed by ion-exchange chromatography on DEAE-Sepharose (Bresolin et al., 2013). The polysaccharides were successfully separated from the enzyme using the chromatography technique employed, resulting in a rise in enzyme activity.

Besides utilizing a modern approach, the traditional method for the bromelain separation is sometimes preferred due to its simplicity with minimum requirement together with easy-to-scale-up process, low energy needs and the consumption of inexpensive precipitants. Purification of bromelain from pineapple waste (stem and bark of ripe pineapple fruit) was accomplished using ethanol precipitation (Soares et al., 2012; Yu et al., 2014). A purification factor of 2.28 was successfully obtained by this method, which resulted in the production of 98% of total enzymatic activity. The resulted enzyme was further stabilized and preserved by utilizing 10% (w/v) glucose as cryoprotector in the lyophilisation process.

4.3. Organic acids

A number of waste or by-products produced from the pineapple agro-industry can be utilized to produce organic acids mainly citric acid, lactic acid and ferulic acid with the aid of fermentation technology. The utilization of pineapple waste for organic acids production is economically significant and reduces environmental problems. Because it is the most basic hydroxyl carboxylic acid and contains only one asymmetrical carbon atom, lactic acid is widely used in the food and pharmaceutical sectors, among others. Both chemical and fermentation synthesis are normally been used to produce lactic acid (Mahamad et al., 2015; Martinez et al., 2013). Due to the increasing demand for naturally produced lactic acid, the fermentation process particularly solid-state fermentation (SSF) method by using various cheap raw materials is industrially preferable nowadays. Fungi were recorded as the most preferable microorganism for solid-state fermentation (SSF) as their super ability to penetrate and utilize the nutrients from solid waste (Joy, 2010; Mathew et al., 2015; Pandey and Pitman, 2003). The production of lactic acid by *Rhizopus oryzae* was achieved by utilizing solid pineapple waste as the substrate in solid-state fermentation technique.

Using the optimum parameter of 80% moisture; pH 6.5; 1 × 104 spores/g of inoculum; waste particle of 3.15 mm; and temperature of 27 °C, 0.0236 g lactic acid/g solid pineapple waste was produced by *R. oryzae* indicating the ability of this fungus to utilize and convert the pineapple waste into a valuable product of lactic acid. The lactic acid bacterium, *Lactobacillus delbrueckii* has also been utilized to produce lactic acid from the liquid and solid pineapple wastes as the carbon source. Anaerobic batch fermentation is used to cultivate the lactic acid bacteria. The lactic acid produced using liquid waste (79%) is much better compared to solid waste (56%) during the fermentation process. The same bacteria have also been used by Sah et al. (2016a) to ferment liquid pineapple waste. In their study, *L. delbrueckii* has been immobilized in a calcium alginate matrix under anaerobic conditions for 72 h. Several parameters regarding immobilization effects were investigated. Highest yield of lactic acid was produced at 37 °C and pH 6.5 after 56 h of fermentation using an immobilization approach with 2% sodium alginate concentration and 0.01 mm bead diameter. This study indicates the efficiency of the immobilization approach for lactic acid production.

Citric acid, a tricarboxylic acid with six carbon atoms is a naturally occurring organic acid that may be found in abundance in nature. Citric acid is generally organic acid that is produced in bulk quantity, and it has been estimated about 75% of this acid is commercially used for processing food industry while 12% for pharmaceutical industries (Prabha and Rangaiah, 2014; Soccol et al., 2006). For example, pineapple waste has been identified as a viable substrate for the manufacture of citric acids. The use of waste from fruit manufacturing is advantageous since it allows for the use of low-grade waste while producing an economically valuable product (Aparecida Damasceno et al., 2016;

Soccol et al., 2006). *Aspergillus niger* was screened for its ability for producing citric acid in the presence of pineapples peels as the substrate and supplemented with various concentrations of sucrose, glucose, ammonium phosphate and ammonium nitrate (Prabha and Rangaiah, 2014). From the study, a solid-state fermentation technique was used for the manufacture of citric acid using pineapple peel as a support system. It has been discovered that under optimal circumstances, a maximum citric acid concentration of 60.6 g/kg of pineapple peel could be obtained.

In addition, *A. niger* MTCC 281 was utilized as the source for the economical manufacture of citric acid from pineapple peel (Prabha and Rangaiah, 2014). The study also represents the impact of alcohols (methanol, ethanol, and butanol) as stimulants on citric acid production where the supplement of alcohols enhanced the degree of citric acid production. The generation of citric acid by *Aspergillus foetidus* ACM3996 in solid-state fermentation was also performed under a support system and a pineapple waste substrate (Pyar et al., 2014; Tran and Mitchell, 2004). The results of the study indicated that pineapple waste outperforms apple pomace, wheat bran, and rice bran in terms of production efficiency. Within 4 days of fermentation, the maximum citric acid content of 16.1 g per 100 g of initial dry pineapple waste was obtained, resulting in a yield of 62.4% based on the amount of sugar used. The moisture content was estimated at 70% and in the presence of 3% methanol. All the above studies suggest the potential usage of pineapple waste for the fungal production of citric acid. The advantage of valorising pineapple waste for significant use in the pharmaceutical and food sectors has been highlighted.

4.4. Prebiotics

There is an increase realization among industry and scientific community that utilizing local sources of waste from various agro-industrial processing industries is a good alternative for prebiotics culture media in minimizing the production cost. The physicochemical properties of pineapple waste show the high potential for it to be used in microbial lactic acid production for the carbon source (Hassan et al., 2014). The nutritional growth source of lactobacilli can be replaced with easily and inexpensively available agricultural industrial waste (Dhanasekaran et al., 2011; Tropea et al., 2014). Besides contributing as carbon source for probiotics, pineapple waste is also a source of nutrient in promoting high growth rate of the good bacteria (Hassan et al., 2014). Therefore, to develop commercial-scale production of probiotics, alternative food sources need to be screened from the local agricultural industry.

According to Sah et al. (2016b) pineapple waste shows a promising alternative for lactic acid bacteria cultivation. Pineapple waste medium shows a comparable performance with the commercial glucose-containing MRS media where no significant difference in the bacteria growth could be seen. However, extensive study is needed for the isolation and characterization of the bioactive compounds extracted from pineapple. A study by Wu et al. (Wu et al., 2021) reported that one of the agriculture by-products (silages) provides a promising source of lactic acid bacteria (LAB) for the application in probiotics and biotechnology industries. More research is needed to see whether it can be used as a helpful culture in the food business. Examples include sodium chloride tolerance, bile salt hydrolases production, animal models in vivo testing, assays to assess the behaviour of isolates from varied food matrices, and exopolysaccharide formation.

5. Advantages of pineapple waste

Pineapple waste is a potential cost-effective source of nutraceuticals and functional foods as it is rich in phytochemicals, nutrients and metabolites that have healing properties on humans such as anti-ageing, anti-hypertension, anti-cancer, anti-cardiovascular and other degenerative diseases (Gupta et al., 2017). As reviewed above, pineapple waste is rich in antioxidants, bromelains and organic acids that play a significant part in the prevention and cure of many diseases. Pineapple waste is also a good source of dietary fibre which has healing properties for colorectal cancer, heart diseases, atherosclerosis, colon cancer, obesity, and diabetes. Dietary fibre is a highly demanded functional ingredient for food products due to its health benefits. As reported by Larrauri et al. (Larrauri et al., 1997), the total dietary fibre (TDF) content of pineapple waste is comparable to some commercial apple and citrus dietary fibres which are 70.6%. In another study, 99.8% of total dietary fibre has been extracted from pineapple core (Prakongpan et al., 2002). With high-level phytonutrients contents, dietary fibre from pineapple waste is highly potential to compete with other commercial dietary fibres in the market.

Pineapple waste has also been utilized in animal feed industry as a natural fibre source. Zainuddin et al. (Zainuddin et al., 2014) produced pineapple plant waste pellets through densification for feeding or ruminant. The addition of a dehydrated pineapple by-product in animal feed was reported to improve the digestibility of nutrients, hence improving the weight gains of goats. This was contributed by the increased nutrient intake by the animal (Costa et al., 2007; Sukruansuwan and Napathorn, 2018). High content of soluble carbohydrates particularly sugars promoted fermentative processes for increased nutrient intake, and pectin content in pineapple waste protected the gastrointestinal mucous and neutralised the bacterial toxins. In non-food industrial applications, pineapple waste is a sustainable fibres source for the pulp and paper industry. Pineapple leaf fibres were investigated as a viable raw resource for paper production. As compared to other lignocellulosic fibres, pineapple leaf fibres include a high concentration of cellulose, exhibit superior mechanical qualities, and contain a low concentration of lignin. These are the desirable properties in the paper industry to produce a high-quality pulp (Laftah and Wan Abdul Rahman, 2016). Several studies reported successful productions of good properties of paper from pineapple leaf fibres. Owing to high natural fibre content and strong mechanical properties, pineapple leaf fibre is also highly potential for other applications such as thermal insulations, sound, plastic reinforcement and as reinforcements in composites (Leão et al., 2015).

Pineapple waste is a natural adsorbent and has been used to remove pollutants from wastewater. It is a sustainable source of adsorbents that serves as an alternative to the existing synthetic adsorbents. Numerous research has reported the potential of various pineapple parts as an adsorbent to remove various dye molecules and heavy metals from wastewater. Most pineapple waste is composed of three key constituents: lignin, hemicellulose along cellulose. FTIR spectrum reflects the structure of the lignocellulosic complex of pineapple waste with the presence of functional groups such as O—H, C—H, ketone and aldehyde carbonyl, aromatic rings, C—O, C=C and C—C—O. The presence of various functional groups contributed to the biosorbent properties of this biomass. Besides, the presence of pores in a honeycomb shape is greatly accredited to the sorbate adhesion properties. A porous and rough internal surface increases the surface area, hence making it a good adsorbent (Chan et al., 2016).

In an aqueous solution, the composition of cellulose and lignin in pineapple waste release hydrogen ions to make the surface area negatively charge (Namasivayam and Sureshkumar, 2006). Hence, raw pineapple waste has a higher affinity to adsorb cationic dyes. Methylene blue was successfully removed from an aqueous solution utilizing leaf powder of pineapple (Kamaru et al., 2016; Weng et al., 2009). Chan et al. (Chan et al., 2016) demonstrated efficient removal of cationic Basic Blue 3 dye from aqueous solution using pineapple plant stem. The authors reported the presence of anionic active sites in the honeycomb-shaped porous structure of the pineapple that attributed to the higher cationic dyes' sorption efficiency. Chowdhury et al. (Chowdhury et al., 2011) and Neupane et al. (Neupane et al., 2015) also reported an efficient removal of cationic dyes (crystal violet dye and Basic Green 4 dye, respectively) from its aqueous solutions using pineapple leaf powder. On the other hand, chemical modification of pineapple is required prior to the removal of anionic dyes to increase its adsorption capacity. Kamaru et al. (Kamaru et al., 2016) demonstrated the enhanced adsorption capacity of anionic methyl orange dye when pineapple leaves were treated with a cationic surfactant, hexa-decyltri-methyl ammonium bromide compared with the untreated one. Besides, pineapple waste in the form of activated carbon was also effective for the decolourisation of methylene blue from wastewater.

The presence of carboxylate ion, aliphatic group, and unsaturated groups like alkene on pineapple surfaces allows adsorption of metal ions through weak interactions (Idris & Suzana, 2006; Ponou et al., 2011). Thus, pineapple waste has also been utilized to adsorb heavy metals from wastewater. Feng et al. (Feng et al., 2018) reported the removal of Zn, Pb, and Cd using pineapple peel primarily through ion exchange interaction or interaction between the metal ions with hydroxyl, carboxyl, carbonyl, methoxyl, amine, and amide groups. Chemical modifications of the pineapple surface have been reported in several studies to generate an active binding site for more efficient removal of metal ions. Gogoi et al. (Gogoi et al., 2018) have described that the chemical modification in pineapple crown leaves by the addition of OH groups improved the chromium ions (Cr(VI) and Cr(III)) adsorption by treatment with acetic acid and hydrogen peroxide. Chemically oxidized pineapple fruit peel biomass also showed enhanced adsorption capacity towards Cd(II) and Pb(II) due to the addition of carboxylic and hydroxyl groups onto the biosorbent surface after the oxidation process (Ahmad et al., 2016). The same observation was also reported by Mopoung and Kengkhetkit (Mopoung and Kengkhetkit, 2016) whereby the stem, leaf, fruit, and mixed waste of pineapple were treated with NaOH. Hu et al. (Hu et al., 2011) reported improved adsorption of Pb^{2+}, Cd^{2+}, and Cu^{2+} to pineapple peel fibre that was chemically modified by the introduction of carboxylic functional groups via reaction with succinic anhydride. Recent research demonstrated that pineapple waste can also be employed to adsorb other compounds such as caffeine from an aqueous solution (Beltrame et al., 2018).

Fig. 4 illustrates the general usage of the whole pineapple fruits including its wastes (non-edible part) for varieties of applications. Due to the huge research being carried out on pineapple waste, many types of products have been developed. This has deeply increased the value of the pineapple waste from ‘nothing’ to ‘something’.

5.1. *Pineapple waste as sustainable food*

Pineapple waste has risen in recent years, contributing to a slew of environmental challenges and energy waste. Because of their useful features and compositions, one of the sustainable approaches that can be done is to convert the residues into valuable and profitable goods. Due to the significant carbon content in pineapple waste, several studies have utilized the residues for dye adsorbent (Dai and Huang, 2016), biofuel (Casabar et al., 2020; Kanakdande et al., 2019; Khedkar et al., 2017) and biogas (Cahyari et al., 2018; Chu et al., 2020; Dahunsi, 2019) production. Bioenergy is the best green energy option which is categorised under renewable energy while the extensive research on it has promote the sustainable development of agricultural wastes. Pineapple waste contains an enzyme called as protease which is an enzyme used for bromelain production (Campos et al., 2019). Researchers have utilized the advantage of the high carbohydrate content (cellulose and hemicellulose) present in pineapple waste to produce several useful products such as bioadsorbents for wastewater treatment and textile industries, biodegradable packaging for food industries, and cellulose nanocrystals (Prado and Spinacé, 2019; Singh et al., 2020; Suwannasing et al., 2015). Moreover, the high sugar content in pineapple waste has made it a potential raw material for wine production (Roda et al., 2017), vinegar (Raji et al., 2012) and organic acid (Zain et al., 2021) manufacturing. The valorisations of pineapple wastes have significantly contributed to the reduction in waste accumulation with new side products can be generated and thus supporting the zero-waste circular economy and applying the concept of waste-to-wealth.

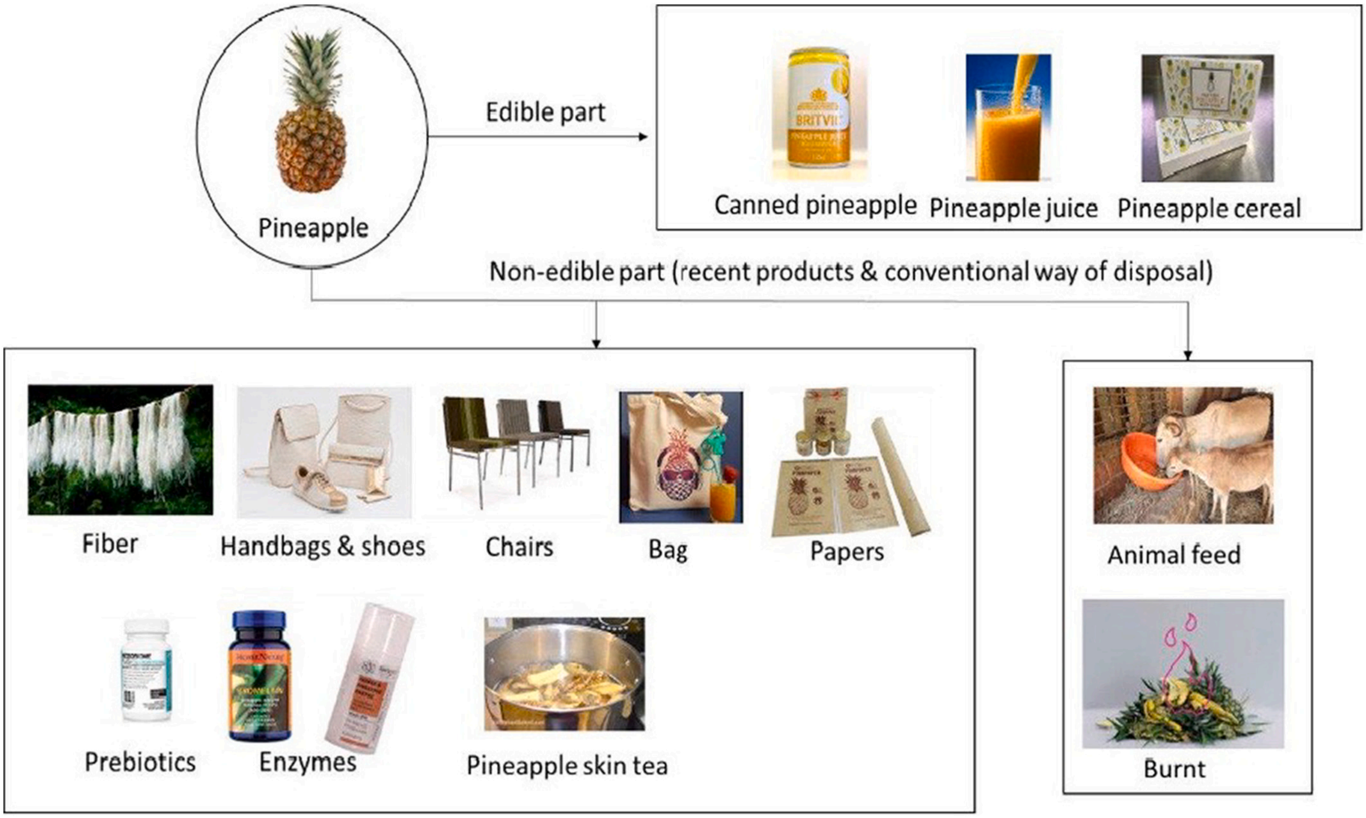

Fig. 4. General usage of the pineapple fruits and its wastes.

6. Conclusions

Pineapple waste from a common agro-industrial processing sector has been investigated as a low-cost source of value-added goods. Several integrated approaches have valorised the pineapple waste to produce more value-added products. This review has simplified some of the recent studies utilizing pineapple waste for various purposes. Although there have been several studies conducted, pilot plant research is still required to optimize the overall processes and thus could fit the industries demand. Despite their enormous potential, food-grade pineapple wastes have not yet received special attention, and as a result, creative processing procedures must be utilized in this endeavour. The habitual practise of recovering value-added goods from discarded pineapple waste would not only save production costs but will also assure sustainability and reduce the anthropogenic effect on an already-vulnerable ecosystem.

CRediT authorship contribution statement

Nur Izyan Wan Azelee, **Nor Hasmaliana Abdul Manas** and **Daniel Joe Dailin**: Supervision, Reviewing and Editing; **Rosli Md Illias**, **Siti Aishah Rashid**, and **Rajinikanth Rajagopa**: Collecting articles and Writing original draft writing and Editing; and **Aizi Nor Mazila Ramli**, **Dr. Mukesh Kumar Awasthi**, **Dr. Balasubramani Ravindran**, **Prof. Soon Woong Chang**, **Prof. Zengqiang Zhang**: Project Administration, Conceptualization and Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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