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Industrial applications of *Ananas comosus* wastes as valuable and utilizable products-A review

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Ananas comosus, tropical fruit from *Bromeliaceae* family, is known for its flavour with major application in a number of industries *viz* juice, canned pulp, fruit candy, jam, jelly, wine, vinegar, bromelain extraction and many more. Large amounts of by-products are generated from these industries in which peel alone accounts for 34-38%. These by-products are discarded as waste and causes serious environmental pollution. Researchers have investigated that these by-products, mainly peels are potential sources of many nutritional and bioactive compounds which exhibits numerous health benefits. The present application of the waste is to convert it into value added products and currently, it is utilized in many industries such as chemical industry, health sectors, food sector, pharmaceuticals, and nutraceuticals. This article summarizes the major applications of *A. comosus* peel at industrial level. 'Industrial applications' is an umbrella term in which biofuel generation; enzyme production; bromelain extraction; cellulose, bacterial cellulose, nanocellulose and nanocrystalline cellulose; nanoparticles synthesis; biorefinery production; superabsorbent hydrogel formation; oil extraction; wine and vinegar production; supplementation; fortification; enrichment etc. terms are embedded.

Keywords: *Ananas comosus*, Bioactive components, By-products, Industrial applications, Nutraceutical, Pharmaceutical.

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Introduction

Ananas comosus, commonly known as Pineapple is a tropical fruit of the *Bromeliaceae* family. According to FAOSTATS (2022) production of pineapple is 27 816 403 tonnes per annum in 1 077 920 ha area of harvesting[1]. Industrial applications of *A. comosus* are extensive like in food and cosmetics industry which accounts for the 35-50% production of biomass of total weight[2-7]. This fleshy fruit encloses a sweet and sour flavour in it which makes it acceptable among humans. Pulp of *A. comosus* is commercially utilized in the manufacturing of juice, canned pulp, fruit candy, fruit drinks, jam, jelly, wine, vinegar, bromelain extraction, beverages, and many other products[8] which is responsible for the generation of massive amount of by-products from which 34-38% contributes to the peel alone. Earlier this biomass was discarded as a waste material, but later many researchers have studied this waste material to combat the problems of environmental pollution and it became evident that this organic solid-waste is full of bioactive compounds possessing many nutritional and therapeutic applications[4,9,10].

Results of the earlier studies have claimed the presence of polyphenols (ferulic acid, chloregenic acid, gallic acid, epicatechin, catechin, trans-cinnamic acid, *p*-coumaric acid, salicylic acid, tannic acid), flavonoids (myricetin), carotenoids (β-carotene, β-cryptoxanthin), terpenoids, alkaloids, saponin, tannins, coumarins, plant sterol, vitamins, minerals (calcium, iron, zinc, manganese) water insoluble fibre rich fraction (celluloses, hemicelluloses, lignin, pectin) and proteins (bromelain) in the peel of *A. comosus*[2,11-17]. The nutritional composition, bioactive compounds along with its antioxidant potentials present in the peels of pineapple are given in Tables 1-3. Occurrences of these bioactive compounds play a key role in the maintenance of healthy life and serves as a preventive agent against countless pathological conditions. Its antioxidant, antimutagenic, antibacterial, antifungal, anti-diabetic, anti-inflammatory, anti-hypertensive, anti-carcinogenic, cardioprotective, hepatoprotective and outstanding pre-biotic potential has been proved earlier by many studies[11,26-31]. Thus, the peel of *A. comosus* is utilized in the formulation of many value-added food products[32-35] as well as used in the synthesis of nanocellulose[36,37], enzymes[38,39], biofuel[40-42], acids[43,44], packaging materials[45,46] etc. The endeavour of

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the present article is to highlight the presence of key metabolites in *A. comosus* peel waste. It could be potentially used as a substrate for creating numerous innovative products serving as baseline with possible potential industrial applications.

Industrial applications of *A. comosus* peel

The massive composition of bioactive compounds enveloped in the peels of pineapple was suggested by analysing its nutritional and anti-nutritional components. Outcomes of previous research have proved pineapple peel as a panacea for environmental hazards by the application of this waste in many industries as raw material for developing low-cost or economic value-added products (Fig. 1).

The major core area of this review article is to explore the utilization of *A. comosus* peel in various industries like vinegar and wine production,

Table 1 — Proximate nutritional value of dried *A. comosus* peels (g/100g dry peel)

Nutrients	Banerjee *et al.*[18]	Toledo *et al.*[19]	Huang *et al.*[20]	Selani *et al.*[21]
Moisture	ND	6.48±0.03	ND	6.60±0.23
Crude protein	5.1 g	3.23±0.13	9.13±0.25	4.00±0.02
Lipids	5.3 g	0.54±0.02	1.57±0.13	1.32±0.10
Ash	4.3 g	1.11±0.10	4.81±0.03	2.45±0.01
Carbohydrates	55.5 g	74.01	42.3	15.92
Crude fibre	14.8 g	ND	ND	ND
Total dietary fibre (TDF)	ND	14.63±0.30	42.2±0.89	69.64±0.28
Insoluble dietary fibre (IDF)	ND	13.55±0.31	36.3±0.79	67.75±0.14
Soluble dietary fibre (SDF)	ND	1.08±0.08	5.90±0.19	1.90±0.14

*ND: Not Documented

Table 2 — Total phenolic content (TPC), Total flavonoid content (TFC) and antioxidant potentials of *A. comosus* peels

Phytochemicals	Toledo *et al.*[19]	Selani *et al.*[21]	Islam *et al.*[2]
Total phenolic content (mg Gallic Acid Equivalent/g dry mass)	2.82±0.60	3.78±0.05	15.69±2.43
Total flavonoid content (mg Quercetin Equivalent/g dry mass)	ND	ND	1.56±0.31
2,2-diphenyl-1-picrylhydrazyl (µmol/Trolox Equivalent/g)	7.14±0.34	5.76±0.12	0.92±0.05
(2,2'-azino-bis (3-ethylbenzthiazoline-6-sulphonic acid)) (µmol/Trolox Equivalent/g)	7.24±0.16	13.46±0.62	0.80±0.01

*ND: Not Documented

Table 3 — Major bioactive compounds present in *A. comosus* peels

Bioactive compounds	Lubaina *et al.*[23] (µg/mg)		Toledo *et al.*[19] (µg/g)	Li *et al.*[24] (mg/100 g dry peel)	Selani *et al.*[21] (µg/g)	Campos *et al.*[25] (mg/100 g dry basis)
	Ethanol	Aqueous	Ethanol:Water (80:20)	Methanol	Ethanol: Water (80:20)	Methanol
Gallic acid	0.14	15.99	ND	31.76±2.28	ND	ND
Catechin	ND	ND	10.30±0.03	58.51±3.59	ND	ND
Epicatechin	ND	ND	ND	50.00±4.39	ND	ND
Ferulic acid	0.15	0.19	ND	19.50±1.93	51.32±2.41	1.02±0.24
Caffeic acid	0.06	0	ND	ND	29.06±1.11	12.56±0.48
p-coumaric acid	0.53	1.61	23.06±0.42	ND	17.10±0.68	0.00±0.00
Chlorogenic acid	0	0.03	ND	ND	ND	0.00±0.00
Catechol	0.02	0	ND	ND	ND	ND
Syringic acid	1.00	0.007	ND	ND	ND	ND
Ellagic acid	1.82	10.17	ND	ND	ND	ND
Myrecetin	0.003	0	ND	ND	ND	ND
Cinnamic acid	0.22	2.14	ND	ND	ND	ND
Quercetin	4.18	5.08	ND	ND	ND	ND
Kaempferol	4.43	2.50	ND	ND	ND	ND
Apigenin	4.90	1.50	ND	ND	ND	ND
Vanillic acid	ND	ND	15.42±0.46	ND	ND	ND
Salicylic acid	ND	ND	13.53±1.32	ND	ND	ND

*ND: Not Documented

Ananas comosus (Pineapple)

↓

Sorting (Removal of damaged pineapple)

↓

Crown cutting

↓

Simultaneous removal of peels and core

↓

Pineapple peel wastes are utilized in the different bioactive constituents (polyphenols, dietary fiber, proteins and enzymes) and value added products through solid state fermentation and extraction

↓

Industrial applications of bioactive compounds includes chemical industries, health sector, food sector, pharmaceuticals and nutraceuticals

Fig. 1 — Flow chart illustrating fate of *A. comosus* peel[47].

bromelain and nanocellulose extraction, preparing cellulose based hydrogels, adsorbent, activated carbons, isolating enzymes etc., and in food sector as meat tenderizer, animal feed, supplemented in several food products due to its excellent nutritional composition[3,48].

Saccharification and biofuel production by using *A. comosus* peel as fermentation medium

Peel of *A. comosus* is a rich source of insoluble dietary fibre and carbohydrates which is responsible for utilizing it in the making of biofuel at fuel manufacturing industries. The enzyme hydrolysate of pineapple peel was extracted by pretreating it for 4 h with water at 100ºC after that enzymatic hydrolysis was done with 0.5% (w/w) cellulase from *Aspergillus niger* then it was used as a medium of fermentation for the production of hydrogen and ethanol by *E. aerogenes* and *S. cerevisiae.* The outcomes of this study proved that the pineapple peel was a significant raw material for the production of biofuel as after 72 h of cultivation with *S. cerevisiae* maximum ethanol production (9.69 g/L) with zero production of hydrogen was observed, whereas cultivation with *E. aerogenes* produced both ethanol (1.38 g/L) and hydrogen (1416 mL/L) after 72 and 12 h, respectively[40].

The potential of *A. comosus* peel for the production of ethanol was explored by enzymatic saccharification and fermentation of obtained sugars like glucose, galactose, xylose, mannose, xylose, and uronic acid with the help of *Saccharomyces cerevisiae* NCYC 2826 strain. Results of the study showed maximum yield of ethanol was reached after 30 hours of synchronized fermentation and saccharification and achieved up to 3.9% (v/v) corresponding to 96% of theoretical yield[41]. Acetonebutanol-ethanol (ABE) was produced using *Clostridium acetobutylicum* B 527 and pineapple peel, an agro-industrial waste. Drying experiments on pineapple peel at a varied temperature ranging between 60-120ºC was carried out. Further detoxification, acid hydrolysis and fermentation processes were used to complete the production of ABE. Acid hydrolysis with the removal of 95-97% phenolics and 10-15% acetic acid during the detoxification process has been proved as most favourable for obtaining maximum amount of sugar (97g/L). Result also suggested 120ºC as the optimum temperature for drying substrates and 55.6% of substrate consumption yielded maximum ABE titre that was 5.23 g/L[42]. Oiwoh *et al.*[49] also studied about the optimization of bioethanol production from simultaneous saccharification and fermentation of pineapple peel using *S. cerevisiae.* The obtained result exhibited the possibility of utilizing pineapple peel for bioethanol production. Itelima *et al.*[50] suggested that pineapple, banana and plantain peels are significant agro-industrial wastes, which could be best utilized for bioethanol production through simultaneous fermentation and saccharification process.

Chu, *et al.*[51] investigated the two-stage biohythane fuel (mixture of hydrogen and methane) which was produced by using two continuous stirred anaerobic bioreactors (CSABR) at mesophilic conditions. Pineapple peel juice with substrate concentration of 64.56 g COD/L was used in the first stage biohydrogen production reactor ($CSABR_H$) and in the second stage of methane production reactor ($CSABR_C$) hydrogenogenic effluent from $CSABR_H$ was directly fed, after integration the optimization of Hydraulic Retention Time (HRT) was examined for two-stage hydrogen and methane production. Effective results were obtained for the production of biohydrogen and biomethane from pineapple integrated with a two-stage bioreactor process for a short duration. Maximum hydrogen yield was 9.3 mL H_2/g COD at HRT 8 h and the maximum hydrogen production rate was 328.72 kg COD/m^3d with HRT 4 h in the methanogenic stage where the yield of methane production was 328.72 kg COD/m^3d. It was concluded that pineapple waste can be effectively used for the production of biohythane (H_2+CH_4) and the two-stage process biohythane production might be proved as successful economic way to generate a novel gaseous fuel from pineapple peel waste juice, operated under high feeding flow rate condition. In addition to these studies, many more researches are done for the optimization and production of biofuel from the pineapple peel waste[52-55].

Utilization of *A. comosus* peels extract as antimicrobial agent

It is proven in many researches that pineapple peel contains many active compounds that kill bacteria but still it is discarded as waste. Wijayati *et al.*[56] observed that pineapple peel contained many phytochemical compounds like flavonoid, tannins, saponins as revealed by UV-Vis spectrophotometer and Fourier transform infrared spectroscopy (FTIR) showed that pineapple peel extract also contains the derivative of dihydroflavonol. Different levels (0.5, 1, and 1.5%) of pineapple peel extract was used in hand sanitizer and applied on hand to test the bacterial activity against *Escherichia coli* and *Streptococcus aureus*. Result demonstrated that all the concentration of peel extract killed the bacteria (*E. coli*) with the inhibition zone of 10, 13, and 15 mm and (*S. aureus*) with the inhibition zone of 10, 15, and 1.5 mm. The highest inhibitory activity was found in 1.5% incorporation of peel extract in the hand sanitizer. The study concluded that by the addition of pineapple peel extract, the quality of hand sanitizer was improved because it contains highest inhibitory activity in comparison to the control. It also passed several tests like organoleptic, pH, homogeneity, and dispersive power.

Alginate based edible film containing natural antioxidants (Total phenolic content) from pineapple peel was used as a preservative to increase the shelf life, for controlling microbial spoilage, colour preservation and providing a barrier to lipid peroxidation of the beef meat. Before incorporation of pineapple peel compound into the alginate based film, various stabilization methods were used including extracted compounds with a hydroalcoholic solvent encapsulated in microparticles. These microparticles were produced by spray-drying pineapple peel juice and particles obtained by milling freeze dried pineapple peel. Highest inhibition of aerobic mesophilic bacteria in the meat sample was found in hydroalcoholic solvent encapsulated films and also retained the colour of the meat sample under refrigerator for 5 days at 4ºC. Result demonstrated that incorporation of pineapple peel antioxidant in the alginate based edible film has the ability to hinder the lipid peroxidation in the meat sample and it also inhibits the microbial spoilage of the meat product[57].

Enzyme production by utilizing *A. comosus* peel as a carbon source

Beitel and Knob[38] produced an enzyme named as β-glucosidases by *Penicillium miczynskii* which is broadly used in the biotechnological processes such as food and feed industries, in production of bioethanol for the hydrolysis of biomass and as flavour enhancer for fruit juices, tea and wine. Further, the authors' studied the effect of time, temperature, pH, cultivation condition, varied carbon sources, and concentration of agro-industrial waste on the production of β-glucosidases along with its biochemical characteristics. The optimum condition for producing β-glucosidases was 3% pineapple peel as the carbon source at constant pH 5.5 for 9 days at 20ºC, yielding 2.82 U/mL. Best enzyme activity was observed at 4.5-5.0 pH and 65ºC. High glucose tolerance capacity of K_i 760mM was also observed. This study suggested that β-glucosidases is a novel enzyme with numerous industrial applications and pineapple peel is an inexpensive agro-industrial that could be utilized for producing β-glucosidases.

From pineapple waste enriched soil, the esterase producing isolates *Bacillus subtilis* E9 and *Bacillus* sp. E46 were identified. For media optimization studies, the *B. subtilis* E9 with 10 U/mg esterase activities was selected for the study. Under optimum conditions such as acetone extract of pineapple peel (1.8%v/v), pH 6.5 with 25 h incubation time enhances the enzyme production (250.50 U/mg). The purity of the enzyme was improved by four-stage purification with specific activity of 384 U/mg and 5.3% recovery. The SDS PAGE was used to determine the molecular weight (45 KDa) and monomeric nature of the enzyme which was finally confirmed by zymogram analysis. Thus, the purified fraction shows the presence of esterase enzyme[39].

Campos *et al.*[58] developed and optimized an easy method to isolate bromelain (BR) from stems and peels of pineapple, generated from industrial applications, through factorial experimental design. Both the crude juices i.e., stem and peel showed high recovery yield of 80-90% of active bromelain. That demonstrated the potential of pineapple waste for producing carrageenan 0.3 g of bromelain from 100 g of pineapple by-product (ca. 0.3 g of BR/100 g of pineapple by-product) with 0.2-0.3% (w/v) concentration of polysaccharide. The research shows that carrageenan could be used as an alternative to inorganic salts and organic solvents as it attains high purity bromelain extracts.

Htaik *et al.*[59] extracted the bromelain enzyme from pineapple waste (peel and core) and used it as a milk clotting agent. With the use of bromelain enzyme, casein was hydrolyzed in the major product tyrosine. After that, antioxidant property of tyrosine was analyzed by using Folin-Ciocalteu's reagent. Spectroscopic method was used to detect the enzymatic properties such as optimum pH and temperature of the extracted enzyme. Pineapple peel was found to yield the highest amount of bromelain enzyme as compared to core. Milk clotting time for 10 mL milk/0.5 mL peel extracted enzyme was 70 min and 10 mL milk/0.5 mL core extracted enzyme was 90 min at 60ºC. It was concluded that bromelain enzymes extracted by pineapple waste were capable of coagulating the milk and can be used as a milk coagulant in the food industry for the preparation of cheese, yogurt etc.

Utilization of *A. comosus* peel as culture medium for cellulose, bacterial cellulose, and nanocellulose extraction

Application and development of bacterial cellulose (BC) and nanocellulose is limited because it costs very high. For making it cost effective and for the disposal of waste, agro-industrial wastes can serve as culture medium in the development of microorganisms as the sole source of carbon and nitrogen. With consideration of this point, BC microfibrils were produced by *Gluconacetobacter swingsii sp.* using pineapple peel juice and sugarcane juice as the culture medium. Hestrin-Schramm medium was utilized as the reference medium. Higher production was observed in pineapple peel juice (2.8 g/L) than reference medium (2.1 g/L). It was illustrated from the result that sugarcane juice and pineapple peel juice are potential sources of carbon and nitrogen. It was proved that agroindustrial wastes could be significantly used as a culture medium for the development of bacterial cellulose[36]. Sardjono *et al.*[37] investigated the effect on crystallinity and morphology of the bacterial nanocellulose (BNC) membrane when using high-pressure homogenizer (HPH) process for production. In this study, the pineapple peel extract was fermented for 10 days with the use of *Acetobacter xylinum.* Result demonstrated reduced particle size upon additional treatment of HPH. Hossain *et al.*[60] isolated cellulosic materials from the skin of various fruits such as coconut, mango, pineapple, banana etc. Afterwards, these cellulosic materials were transformed into the derivatives of carboxymethyl and acetate celluloses. Analysis of their characteristics suggested that these by-products could be utilized commercially and ultimately decline in the environmental pollution could be observed.

For extracting nanocellulose, pineapple peel biomass was utilized as raw material. It was a two-step hydrolysis process. Initially, HCl hydrolysis of cellulose from pineapple peel was done to get microcrystalline cellulose. Subsequently, H_2SO_4 hydrolysis was done to get small fragments and minimize the content of lignin. To assess the time in which the particle size reduced, a time dependent study was conducted by analysing the contact time with H_2SO_4. After 60 minutes of exposure to 65 wt% H_2SO_4, nanofiber-like cellulose was extracted[61]. Nanocellulose extraction from *A. comosus* peel and its ability to reinforce for gellan gum was examined by Dai *et al.*[3]. After bleaching and treating with alkali, the sample was characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) tests and result demonstrated the continuous removal of non-cellulosic components without destructing the structure of cellulose. Imaging through atomic force microscopy revealed that nanocellulose exhibits a needle-like structure which measures 15±5 nm on an average diameter and 189±23 nm length. A higher thermal stability was observed in the fibres that were obtained with bleached and alkali treated pineapple peel than the untreated ones. It was described from the rheological results that with an increment in the nanocellulose content, the viscosities of nanocellulose or gellan gum solutions were also increased. Light transmittance and mechanical properties of prepared film were characterized with the help of SEM, FTIR, and XRD. It showed that thermal stability of gellan gum films introduced with nanocellulose was increased whereas the light transmittance values were decreased. Tensile strength of neat gellan gum film and gellan gum with 4% nanocellulose incorporation was compared and the outcome showed 48.21% improvement in the tensile strength of nanocellulose overloaded gellan gum films.

Nanoparticles synthesis using *A. comosus* peel and its film application

As a cost-effective and environment friendly approach, recent researches are moving towards green nanotechnology with the application of food wastes due to its great biomedicinal potential. Coming towards this approach, *A. comosus* (AC) peel extract was utilized in the formulation of silver nanoparticles (AgNPs). FTIR, SEM, XRD, UV–visible spectroscopy, and energy-dispersive X-ray spectroscopy (EDX) analysis were undertaken to know the properties of the nanoparticles generated. Confirmation test for the formation of AgNPs was observed with the alteration in colour due to Plasmon resonance by UV–visible spectroscopy at 480 nm. Synthesized AC-AgNPs underwent biomedical evaluations and its antibacterial, antidiabetic, antioxidative and cytotoxic potential against HepG2 cells were analyzed. In a dose dependent manner it was found effective for cytotoxic activity against HepG2 cells and for glucoregulation, at very low concentration. Significant antioxidative activity and average antibacterial potential against four tested foodborne pathogens were also analyzed. Highlights of the overall study result was as AC-AgNPs are potentially effective for treating acute illnesses, for the formulation of drugs as well as in the dressing of wounds or to prevent from bacterial diseases[11]. Poadang *et al.*[62] also synthesized and characterized Ag-NPs as potentially active agents, working against pathogenic foodborne bacteria mainly *Pseudomonas aeruginosa* and *Staphylococcus aureus.*

In another study, Basri *et al.*[4] synthesized zinc oxide nanoparticles (ZnO-NPs) with the application of pineapple peel and evaluated the effect of temperature on the shape and size of ZnO-NPs along with its antibacterial activity in starch films. The micrographs drawn between 28 and 60ºC clearly displayed the effect of synthesis temperature on the shape and size of ZnO-NPs. Spherical and rod shaped NPs with 8-45 nm diameter and flower rod shaped NPs with 73-123 nm diameter were synthesized at non-heated conditions (28ºC) and heated (60ºC) conditions, respectively. By the means of film casting method, ZnO- starch nanocomposites films consisting of 1, 3, and 5 wt% of Zn-ONPs were formulated and their antibacterial potential was checked against Gram-negative and Gram-positive bacteria by disc diffusion method. Results demonstrated an increased zone of inhibition for Gram-positive bacteria (mainly *Bacillus subtilis*) with an increase in ZnO-NPs concentration from 1-5 wt%.

Utilization of *A. comosus* peel for value addition in biorefinery production

For value addition, *A. comosus* peel was incorporated as an unfamiliar source of hemicellulose (31.8±1.9%). For extracting hemicellulose, an alkali-based method was applied in which incubation of peels was done for 16 h at varied concentrations of alkali (5, 10, and 15% w/v) and temperature ranging from 35 to 65ºC. At a concentration of 15% alkali for 16 h at 45ºC temperature, maximum hemicellulose (95.9±2.0%) was obtained. Whereas at higher incubation temperature (65ºC), minimum yield (81.7±3.7%) was noticed which led to disintegration of hemicellulose structure because of temperature-time combination. A large severity factor and a higher yield (96.6±0.3%) were also noticed with low severity factor (65ºC for 4 h). At the end of 1.5 h, hydrothermal pretreatment at 121ºC and 15 psi pressure, maximum yield of 87.6% was observed with 10% alkali. For the production of xylose oligosaccharide (XOS), extracted hemicellulose was hydrolyzed enzymatically and optimum pH, time, temperature, and enzyme dose (U) was obtained. Xylose-rich liquor (91% xylose) was obtained through the hydrolysis of pineapple peel with 0.5% dilute nitric acid in 1 h. Xylitol, a potential chemical could be obtained by conversion of xylose-rich liquor[63].

Superabsorbent hydrogel synthesis with the incorporation of *A. comosus* peel cellulose

To convert waste into worth, peel of *A. comosus*is is being utilized industrially in many forms. Hydrogel synthesis is one of them. Dai and Huang[2,64] worked for the synthesis of superabsorbent hydrogel with the incorporation of acrylic acid and acrylamide in the carboxymethyl cellulose of pineapple peel and introduction of carclazyte.

For separate or simultaneous removal of lignin and hemicelluloses from pineapple peel, it was processed hierarchically with water (WT-PP), alkali (AT-PP), bleaching (BT-PP) and bleaching alkali (PPC). Further, through facile dissolution-regeneration process in ionic liquid, these processed peels of pineapple were formulated into hydrogels; WT-PPH, AT-PPH, BT-PPH, and PPCH, respectively. Comparison and investigation of the structure and congo red (CR) adsorption ability of the hydrogels were done. Maximum observed adsorption capacity was 114.94, 77.52, 138.89, and 75.19 mg/g for WT-PPH, AT-PPH, BT-PPH, and PPCH, respectively. Formulated hydrogels also showed its good reusability and pH dependent behaviour during the process of adsorption[65].

Enzymatic extract of pineapple peel is used to convert it into hydrogel beads due to its low cost, ease of preparation, and time factor. Therefore, enzymatic extract of pineapple peel containing bromelain was prepared with two varied methods *viz* with mechanical grinding for 9 days and without mechanical grinding. After that these extracts were immobilized on hydrogel beads for utilizing it as a biocatalyst for generating energy interest esters. Result demonstrated the 1.95 mg/mL of protein content was obtained with 6 days of mechanical grinding. On the other hand without grinding, 1 day extraction attained the best index esterification activity for lauric acid (1.8 U/mL); and 28.8% of maximum protein yield was obtained with mechanical grinding and 1 day extract for the immobilization of hydrogel beads. Esterification for 48 hours of the dodecanoate n-propyl 95.1% was declared as the best conversion performance in the biocatalysis of fatty esters[66].

Production of bio-based polymers from pineapple peel wastes

One of the exclusive classes of polymers includes biodegradable and biocompatible polymers. The standard method for producing bio-based polymers from pineapple peel requires biopolymers extraction from agricultural wastes. Initially chemical composition of polymer yields was predicted through carbon to nitrogen (C/N) and carbon to phosphorus (C/P) ratios. The pineapple peels were fermented using ammonium sulphate or dipotassium phosphate and later hydrolyzed with H_2SO_4, following centrifugation at a rate of 4000 rpm or higher for the extraction of biopolymers. The final product was characterized by instruments such as GC-MS, NMR, and FTIR. Furthermore, the yield of biopolymer was influenced by pH optimization and time which were 9 and 60 hours. Thus, the natural bacterial synthesis methods were complemented by chemically induced fermentation showing yield data[67].

Jatav *et al.*[68] assessed the antimicrobial and antioxidant properties of polyphenol-rich chitosan-pineapple peel film to be used as an active food packaging film. Higher antioxidant activity was reported in ethanolic extract of pineapple peel (PEE) enriched chitosan film as compared to methanolic extract of pineapple peel (PME) enriched chitosan film due to quercetin, kaempferol, and ferulic acid in both the extracts. Significant inhibitory zones were also assessed against four foodborne bacterial strains *i.e., Bacillus cereus, S. aureus, E. Coli*, and *Salmonella typhimurium.* Higher log reduction against all the four bacterial cells was noticed in PEE and PME chitosan fims at ≤5 and ≤6 logs CFU/mL, respectively. Whereas, pure chitosan film expressed lower log reduction for all four bacterial cells after 24 h at ≥7 log CFU/mL.

Extraction of oil from *A. comosus* peels waste

Orodu and Inengite[69] extracted oil from the peels of *A. comosus* for better utilization of waste products and checked it for human consumption. Collected samples were dried in the sun for 5 days and oven dried for 1.30 h then grounded. Powdered sample was kept in n-hexane solution for 72 h, then after evaporating the solvents it was kept in a water bath. The obtained result shows 226.27 mg/KOH/g of saponification values (SV), 2.068 mg/KOH/g of free fatty acid (FFA), 37.4355 g/100g of iodine value (IV), 4.11532 mg/KOH/g of acid value (AV) and 7.666 meq/Kg of peroxide value (PV) which exerts high AV and FFA; low SV and IV and; adequate range of PV as compared to the standards given by the Nigerian Industrial Standards (NIS). Overall, it was advised as good for human consumption as well as adequate for industrial purposes.

Acid production by utilizing pineapple waste

Wide ranging application of acids in food, pharmaceutical and chemical industries has suggested its economic and environment friendly production by utilizing agro-industrial wastes. On the basis of this, by-products of processed pineapple were fermented by *Aspergillus niger* to produce citric acid. Results obtained through central composite design (CCD) approach had confirmed the optimum operating conditions as temperature 30ºC, fermentation time 50 h, pH 4.3, methanol 3% (v/v) and concentration of glucose 38 g/L with a yield of 15.51 g/L of citric acid. This study proves that pineapple waste could be utilized as a low-cost substrate for the production of citric acid[43].

Oxalic acid is also produced through fermentation and the effect of several factors on its production could be noticed. Effect of magnesium sulphate ($MgSO_4$), potassium dihydrogen phosphate (KH_2PO_4) and sodium nitrate ($NaNO_3$), three independent variables, and their mutual interaction was investigated on the production process of oxalic acid using pineapple waste through Box Behnken Design (BBD). Results of the study[44] revealed maximum oxalic acid value (20.73 g/L) was realized with the optimum condition for production as 0.77 g/L of KH_2PO_4, 1.78 g/L of $NaNO_3$, and 0.09 g/L of $MgSO_4$.

Formulation of pineapple waste supplemented fermentation substrate

The physical, chemical, and elemental properties of gold honey variety pineapple waste and Sachainchi sub-products (SIS), suggest its best utilization in the formulation of supplemented fermentation substrate (SFS). It showed high micro and macro nutrient content mainly of carbohydrates and proteins, which provides optimum conditions for the development of *Weissella cibaria,* lactic acid bacteria. After the physicochemical, proximal, and elemental analysis of fresh pineapple peel and core (FPP, FPC), powdered pineapple peel and core (PPP, PPC), mixed core and peel of pineapple (MCPP), SIS, SFS and *W. cibaria;* effect of combined pre-treatments (homogenization and heating to boiling point) on the concentration of reducing sugar in SFS (g/L) was evaluated. The obtained result demonstrated a higher total sugar content in FPC with 7.21% than 6.65% in FPP; SIS obtained high crude protein content with 56.70%; and 6.50:1.00 ratio of $C:N_2$. However, combined pre-treatments followed by hydrolysis of SFS for 5 h get the highest concentration of reducing sugar i.e., 4.44±0.29 g/L. Finally, it was concluded that SFS showed efficiency of these wastes for the adaptation of *W. cibaria* with 2.93 g/L of biomass production and 9.88 log CFU/mL of viability. The study gives perspective for large-scale application of pineapple and sachainchi waste to produce unconventional fermentation substrate[70]. In order to fulfil the increased demand of yeast at global level, it is advisable to produce a high quantity of yeast through a cheaper and simple process. Presence of various minerals in pineapple waste favours to support the fermentation process for the production of yeast. Initially, pineapple waste as feedstock is pre-treated and later it undergoes thermal hydrolysis for the conversion of sucrose to glucose. Finally, downstream and fermentation processes were accomplished to obtain yeast. It was clear from the study that yeast products could be produced locally with the utilization of pineapple waste as alternate substrate[71].

Preparation of green packaging material by using pineapple waste

In a study researchers developed 100% biodegradable disposable paper cups by using fruit peels (pineapple peel and orange peel) along with Mauritian hemp (*Furcraea foetida*). Different ratios of hemp: Pineapple peel and hemp: Orange peel were taken to produce paper cups by using soda pulping followed by vacuum moulding. Then the biodegradable cups prepared by fruit peels and hemp were compared by relevant standards in terms of appearance and texture, tensile strength, burst strength, water leakage, weight load, and biodegradability. Colour and base stability of all cups were compatible with control but the characteristics of hemp: Pineapple peel (40:60) is more similar to standard one with no cracks and variation rate of weight load. Biodegradable cups coated with beeswax with the thickness of 0.70 mm holds the cold water for a minimum 30 minutes without any leakage. It was concluded that fibre extracted from fruit peels and hemp leaves can successfully be utilized for the formation of biodegradable, eco-friendly disposable cups which requires less energy and raw material therefore it enhances the economy by using all these waste products in a value added product and also helps in reducing the environmental pollution[45].

Food packaging and wrapping is mainly done by plastic films that are deleterious to health, it takes longer time for degradation and also increases environmental pollution. In a study, pectin extracted by pineapple waste mainly rind and sodium alginate extracted by seaweed was used to prepare an edible film for food packaging. Preparation of cross-linked polymers through pectin and sodium alginate with bio-based acids like citric acid and tartaric acid was used and then all these cross-linked films were detected by different analytical methods such as thermogravimetry, FT-IR and scanning electron microscopy (SEM). Cross-linked polymers improve the tensile strength of the films; and contain good chemical resistivity, thermal property, antibacterial activity, flexibility, biodegradability and transparency. The mice feeding method was used to detect the edibility of the cross-linked films. It was concluded that cross-linked polymers are edible and proved as a good substrate for plant growth; a green wrapping material to improve the shelf life of food products mainly, chocolates and Indian vegetable puff; were effectively converted as edible packaging material[46].

Addition of *A. comosus* peel as functional ingredient in the formulation of value-added products *Biscuits*

The great nutritional load enclosed in the peel of *A. comosus* and extensive consumption of biscuits in developing countries had given the idea of incorporating pineapple peel flour in biscuits as a functional ingredient and enriching its nutritional value. The nutritional and sensory quality of biscuits, prepared with the blends of wheat and pineapple peel flour, at different ratios of wheat-pineapple peel flour (90:10, 80:20, 70:30, 60:40, and 50:50) was assessed by its functional, chemical, mineral and microbiological evaluations against the control group (without pineapple flour) using standard methods. It was clear from the result obtained from sensory evaluation that addition of pineapple flour in 90:10 ratios was best from all other combinations while colour, crispness, aroma, taste and acceptability were high for all the combinations. Obtained result also proved that with an increment in the proportion of pineapple peel flour, the properties of water and oil absorption was also increased along with the increment of minerals (sodium, potassium, calcium, copper, and iron) and proximate composition except carbohydrate content which was decreased. Overall it shows the possibility of formulating more nutritious biscuits using pineapple peel flour as a functional ingredient[32].

Steamed bread

Due to the high percentage of cellulose (35%), hemicellulose (19%) and lignin (16%) present in *A. comosus* peel, it could be utilized as a potential source of dietary fibre[27]. Incorporation of pineapple peel fibre (PPF) in dough and steamed bread resulted into less extensible and stiffer dough with or without fermentation and with an increase in PPF substitution (0-15%) the gumminess and hardness of bread was also increased while decrease in the elasticity, cohesiveness and specific volume of bread was observed. Results obtained from sensory evaluation declare that the steamed bread enriched with 0-10% PPF was more acceptable (4.50-4.87 score) than enriched with 15% (3.45 score). In summary, it was suggested that to increase the consumption of dietary fibre, wheat flour in steamed bread could be substituted by 5-10% of PPF[33].

Cookies

Cookies were formulated by partial substitution of wheat flour with pineapple, melon, and apple peel powders at a concentration of 5, 10, and 15%. Investigation of its physicochemical evaluation states that cookies enriched with 15% melon was nutritionally higher than others while sensory evaluation proved the higher acceptability of pineapple peel enriched cookies with 15%. From the sensory point of view, the colour of cookies was slightly darker. Even then due to the addition of by-product of pineapple a positive effect on consumers with buying intention was noticed. Hence, fruit peels are a potential source of low-cost value added items at industrial level[34].

Cereal bars

Cereal bars are made up of cereals, fruits, nuts, and sugar along with other ingredients that are rich in nutrients and provide many health benefits. Incorporation of pineapple peel flour into a new product enhances the nutritional quality of food product and reduces the waste generated by the juice and pulp industries. Damasceno *et al.*[35] developed cereal bars enriched with pineapple peel flour with different ratios (0, 3, 6, and 9% flour) and examined their ash, moisture, protein, fat, carbohydrate, and crude fibre contents. These experiments showed that highest crude fibre content and textural stability was found in the highest amount of pineapple peel flour incorporated in cereal bars. Technological characteristics of these cereal bars like lower pH and higher acidity contribute to increase the microbiological quality and also increase the shelf life of the bars. About 6% incorporation of pineapple peel flour showed no significant difference between sensory quality and textural profile so that incorporation of pineapple peel flour up to 6% is acceptable. Result demonstrated that incorporation of pineapple peel flour in the cereal bar is good for health and also cuts down the generation of waste.

In another study, de Carvalho *et al.*[72] prepared a cereal bar from Brazilian nuts such as *chichá*, *sapucaia* and *gurguéia* in different formulation ratios which varied in their processing as pineapple peel powder and vegetable fat were used. Highest acceptability was found in formula having 4 g of hydrogenated fat and 5 g pineapple peel powder/100 g cereal bar by using global appearance parameters. *chichá*, *sapucaia* nut cereal bars had more acceptability than *gurguéia* cereal bars. It was concluded that all three almonds of *chichá*, *sapucaia*, and *gurguéia* with pineapple peel were feasible and successful innovations to develop nutrient rich new formulas of cereal bars.

Yogurt

Fruit waste contains many nutrients like protein, carbohydrate, vitamins, and minerals which are important for the growth of probiotic bacteria. In a study, 1% (wt/vol) pineapple peel powder was supplemented in yogurt with the probiotic strain *Lactobacillus casei*, *Lactobacillus acidophilus*, and *Lactobacillus paracasei* Spp. at 4^{o}C for 28 days. Plain and probiotic yogurt were prepared by supplementation with or without pineapple peel, stored for 28 days and evaluated for their antioxidant and anti-mutagenic activity during the growth of probiotic strains. It was observed that higher degree of proteolysis, antioxidant, and anti-mutagenic activity was found in the synbiotic yogurt as compared to plain yogurt. It was concluded that supplementation of pineapple peel and probiotic strains in the yogurt was served as a functional ingredient that improved the nutritional and functional quality of the yogurt[26,73,74].

Gummy candies

Romo-Zamarrón *et al.*[75] prepared a gummy candy incorporated with pineapple and papaya peel powder dehydrated by hot air and freeze drying method with different particle size and used as an ingredient in the gummy candies as well as examined their pH, water activity, soluble solids, colour, texture, and sensory attributes. It was found that incorporation of 5 g/100 g pineapple and papaya peel powder each were acceptable with stable acidity, pH, colour, instrumental texture and also increased the flavour. Besides these, it reduced the caloric content of the gummy candy. Freeze dried peels with smaller particle size have better sensory and textural attributes because it was easily homogenized and emphasized the gel structure and created a better colour to the gummy candy. Results showed that both control and supplemented gummy candies were acceptable on sensory evaluation but control samples had the highest score in all attributes.

Sausages

Fruit peel is an agro-industrial by-product and a good source of dietary fibre and bioactive compounds providing excellent physiochemical and structural appearance to the cooked meat products. In a study, the functional property of cactus pear peel flour and pineapple peel flour was evaluated by using it as a fibre source in cooked meat products. Cooked sausages were inoculated with thermotolerant lactic acid bacteria and the result demonstrated that both fruits peel contains bioactive compounds (antioxidant, fibre, and probiotics) which improved the growth of thermotolerant lactic acid bacteria in the cooked sausages during storage. It was concluded that incorporation of both fruit peels with the inoculum of thermotolerant probiotic lactic acid bacteria can be a good opportunity to prepare a symbiotic meat product[76,77].

Use of *A. comosus* peel for wine production

Dry wine production is another way of utilizing pineapple peel at industrial level. Graham *et al.*[8] produced superior quality wine, with an alcohol content of 13.40-13.57% which is higher than the requirement of table wine (9-12%). Four varieties of wines were produced first by treating with pectolase; second by treating with antioxidants; third by treating with both pectolase and antioxidants and the last one control without any treatment. Acceptable wine was obtained from two varieties *viz* pectolase and antioxidant treated. Preference was given to pectolase treated wine due to its colour, flavour, aroma and clarity. Addition of antioxidants resulted in lighter colour wine and delayed process of clarification. A fruity flavour and clearest wine was produced with the addition of pectolytic enzyme. According to the results, pH value was optimum (3.50) for all the four wines and it was proved as microbiologically safe by total plate count (<10 cfu/mL of wine). Overall, pineapple peel was considered as a significant raw material for wine production.

Applications of *A. comosus* peel in the production of vinegar

Peel of pineapple has also been used for the vinegar production[78-80] which is used as wound dressing agent, food preservative, and disinfectant. The initial step for the production of vinegar from pineapple peel was saccharification and then it was observed for the possibility of producing the highest yield of reducing sugar from pineapple peel and core. Conversion of fibres to monomeric sugars was evaluated after the enzymatic saccharification with different enzymes such as cellulolytic, amylolytic, and invertase. Highest total reducing sugar (more than 100 g/kg of fresh peel) was yielded in 100 g of waste fresh weight (fw) of 0.025 mL of thermostable α-amylase, before a 10 min pre-treatment at a pressure of 143.27 kPa. Then incubating at 50°C for 24 h with the addition of 6 g cellulase/kg_{fw}, 1 g hemicellulase/kg_{fw}, 0.05 g pectinase/kg_{fw}, and 0.05% of pullulanase and glucoamylase (V_{enzyme}/kg_{fw}). Further, the samples were incubated at 50°C for 3 h with 0.05 g of invertase/kg_{fw}[(Ref. 81)]. Fermented pineapple peel was used to prepare vinegar by two-stage fermentation with baker's yeast and the results analyzed 1.08 g/mL of density, 2.80 of pH value, 0.0477 acid value, 1.390 of refractive index, 0.94cp viscosity, and 4.77% of acetic acid value. Hence, the results demonstrated that all the parameters were favourable and well accepted as compared to standard values. Thus, it was concluded that the use of pineapple peel for manufacturing of vinegar not only provides health benefits but also reduces environmental pollution[82].

Discussion

In the present scenario, approximately 89 million tons of food waste is produced in the European Union, in the upcoming years, this value may be raised up to 40 fold. Different organizations have given different values for these food losses. According to Food and Agricultural Organization, from the total production in India, 40% is accounted as waste. While, Food Corporation of India (FCI) considered that this loss may range between 10-15% of total. Around 12 million tons of fruit loss from total production, is estimated by The Ministry of Food Processing Industries (MFPI)[77]. By keeping this data as base, it is utmost important to manage this loss by converting into value-added products for sustainable development. Utilizing this waste, especially peel in the formulation of value-added products can prove as a novel business opportunity, providing economic, environmental and social benefits. However, these wastes are utilized somewhere but due to lack of technological advancements; it is not utilized to its full potential. *A. comosus* peel shows potential ingredients to develop such a value-added commodity in different sectors[82-84].

Conclusion

It was concluded that pineapple peel is a good source of bioactive compounds and dietary fibre content which could be utilized as a significant source for many industrial purposes. Commercially, it is utilized in the health, chemical, food, nutraceutical and pharmaceutical sectors. These products formulated at industrial level, exhibit a great therapeutic potential. Therefore, peel of pineapple could be utilized as an economic and environment friendly raw material for numerous activities. Utilizing pineapple peel in different food products as a functional ingredient has been proven to be the best.

Conflict of interest

The authors have declared no conflict of interest.

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