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A Bio-refinery Approach from Pineapple in the Context of Non-Technified Crops: The Choco-Colombian Region

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ABSTRACT

A pineapple bio refinery that could be adapted to the geographical and cultural conditions of non-technified crops, *i.e.*, the Choco-Colombia region is described. Some characteristics of the region such as the geographical conditions and the relative backwardness related to economic, social, cultural and infrastructure conditions, lead to a relatively high waste of harvested pineapple, with a negative economic and environmental impact. Such situation is also identified in several areas dedicated to pineapple cultivation all over the world, where the pineapple crop usually does not reach export quality and high amount of fruits could end up as wastes. This document initially presents a description of the main generalities of pineapple cultivation and its market. Then, some of the main products of pineapple and its residues are described. Finally, the peculiarities of pineapple cultivation in the Choco-Colombia region are presented and a possible scenario of pineapple biorefinery for that region is proposed. This contribution is expected to be an adequate review material for analysis and decision making in technical and economic feasibility studies to obtain various products from pineapple residues in non-technified crops, motivating both public and private sectors to invest and promote agro-industry initiatives from pineapple waste.

Key words: Added value products, Pineapple biorefinery, Waste valorization.

For developing countries, the competitiveness of local and international markets, as well as current trends in the care and sustainable preservation of the environment, make it necessary to innovate in technologies and production chains to guarantee survival of small and medium enterprises; such situation includes the productive chains related to agro-industry. In this context, the cultivation and commercial exploitation of native products, including the tropical fruits of easy and rapid growth in countries as Colombia, has shown over the years lack of opportunities related to the valuation of derivative by-products (Murcia, 2020). In Colombia, around 30,000 hectares of pineapple are cultivated, with an annual production closer to 1 millon tons of fruit (MADR, 2019). Of the total pineapple produced in the country, approximately 56% is destined for consumption as fresh fruit and the rest is exported or processed to obtain derived products (for example, frozen sliced pulp, canned juice or concentrate) that are sold mainly in local markets (MADR, 2019). When the pineapple is intended for consumption as fruit or to obtain products derived from its pulp, approximately 50% by weight of the fruit is discarded, represented by the residual pulp, the crown, the shells, the heart (center of the fruit) and the stem (Murcia, 2020). In addition, in some regions of the country, geographical conditions and relative backwardness related to economic, social, cultural and infrastructure conditions lead to a relatively high waste of harvested fruit, called rejection pineapple, which consists of fruits that do not satisfy the minimum standard for its commercialization, as well as the fruits that are not commercialized before losing its organoleptic properties due to its natural deterioration. As an example of such situation it is the Choco-Colombia region, a sylvatic region located to Norwest of Colombia (5°42′ 00′′ N 76°40′ 00′′ O), Fig 1. Each year, the Choco-Colombia region produce around 8,000 tons of pineapple, of which approximately 50% is transformed into waste (Murcia *et al.*, 2019; 2020). Due to the conditions associated with the level of development of that region of the country, those wastes ended up mainly in the open dumps or in the water sources, turning them into a serious environmental problem given the biological and chemical oxygen demand of this type of waste (Murcia *et al.*, 2019; 2020).

Today and for more than 50 years, several studies have focused on the valorization of each and every part of the pineapple (pulp, residual pulp, peel, heart, stem and leaves), which thanks to sugars, vitamins and growth factors that they possess can be used as a source of various metabolites or products of interest or as a low-cost substrate in different processes (Banerjee *et al.*, 2018; Gil and Maupoey, 2018;

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Roda and Lambri, 2019). Alternatively, the thermochemical transformation of pineapple waste can be considered for its energy use or for the production of gaseous products (such as synthesis gas or methane), liquids (such as alcohols, aldehydes or synthetic fuels) and solids, such as bio char, which can be used as an adsorbent or as an additive for soil remediation (Pérez *et al*., 2015). The diversity of potential products that can eventually be derived from pineapple residues allows considering the integral study of their use under the concept of biorefinery, whose strategy is to adapt and integrate multiple processes (physical, chemical and biotechnological) to obtain a diversity of products that maximize the use of raw materials (pineapple and its residues), obtaining a greater quantity and variety of valuable products and minimizing the generation of waste and its negative environmental impact (Batsy *et al*., 2013; Pérez *et al*., 2015).

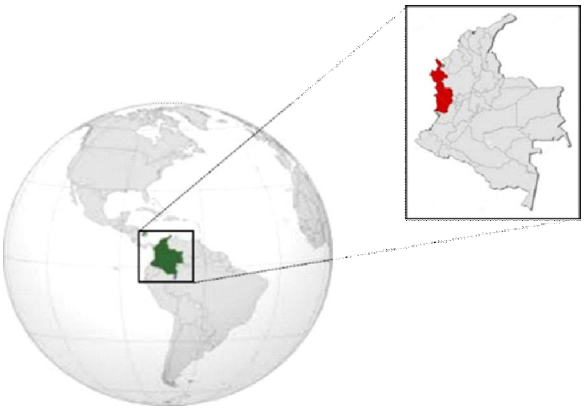


Fig 1: Geographic location of the Choco-Colombia region.

In recent literature there are different studies that compile important aspects related to the recovery of pineapple residues. For example, in the revision of Banerjee *et al*., (2018), different configurations or schemes involving thermal processes (such as gasification and carbonization), chemical processes (such as hydrolysis, acid hydrolysis and basic extractions) and biotechnological processes are included to obtain a diversity of products such as bromelain, vanillin, xylose, xylitol, celluloses, glucose and activated carbon, among others, using pineapple fruit, peels and leaves as raw material. The products obtained have direct applications in industries or markets related to fuels, water purification, catalysis, pharmaceutical products, food and therapeutic products, among others. Other schemes compiled by these authors (Banerjee *et al*., 2018) give greater importance to the extraction of juices, fibers,

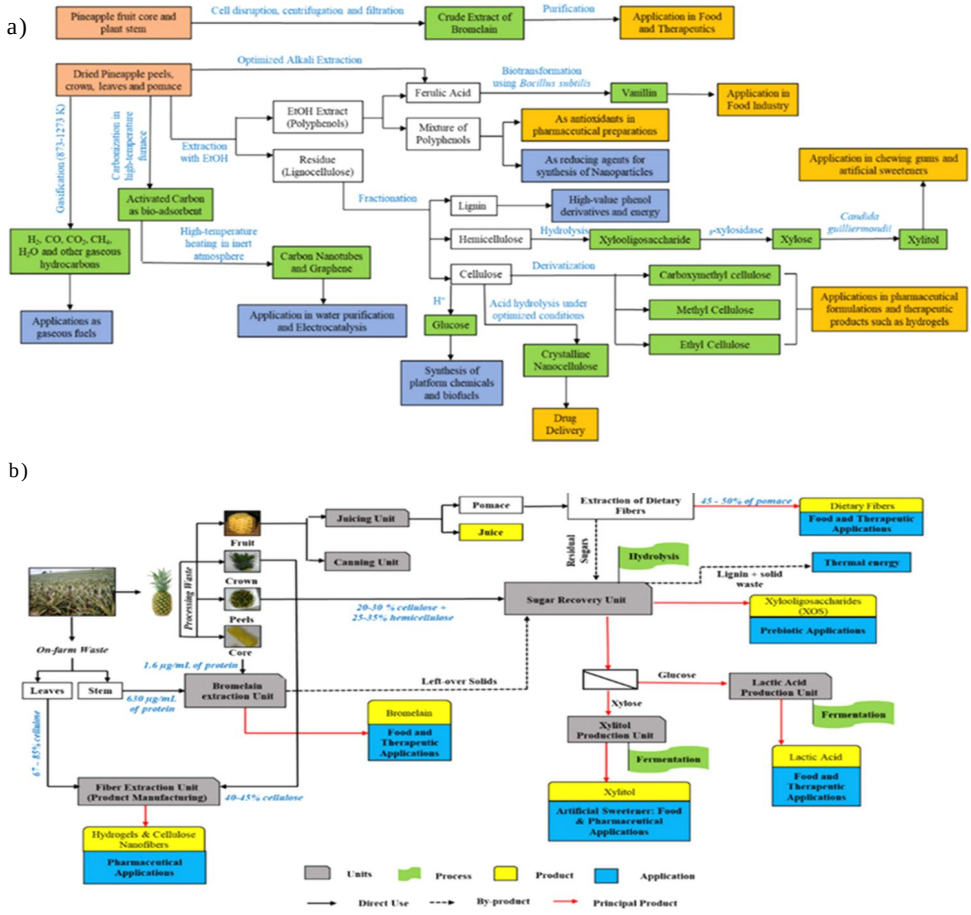


Fig 2: Example of two different pineapple biorefinery schemes, a and b, taken from (Banerjee *et al*., 2018).

oligosaccharides, lactic acid, among others, using different processes or technologies on the same raw materials. See Following the same concept, Gil and Maupoey, (2018) propose the use of pineapple industrial waste to obtain bromelain, bioethanol, supplements for animal feed and fertilizers, among others Fig 3.

Despite the variety of processes and technologies of different nature that can be adapted for the integrated transformation of pineapple or its waste, the literature consulted does not emphasize the geographical, demographic or social particularities of the regions where the pineapple is grown and that may be convenient (or inconvenient) for the appropriate implementation of selected technologies or the production of specific materials. According to Reinhardt and Rodriguez (2009), several factors must be considered when adding value to pineapples through agro industrial processing: the integration of the producer and the processing industry, the type of fruit variety compared to the application, the product portfolio, the processing technology, the logistics, marketing and long-term planning, among others. Even the socio-economic status of pineapple growers (Dickson *et al*., 2002; Nanda *et al*., 2012) as well as trends related with growth and instability of pineapple production (Singh *et al*., 2016) should be considered. As an example of the above, it could be obvious that for a technically grown pineapple crop with a high production volume, it can be assumed the sufficient availability of pineapple crowns to justify a sugar recovery unit such as the one included in the biorefinery scheme in Fig 2b, but for the cultivation of pineapple in small and non-technical farms, the collection of pineapple crowns can represent economic costs that limit its viability and may be more appropriate to use the crowns as a supplement for animal feed or to obtain fibers in a small-scale production. Similarly, any process or product considered in the bio-refinery schemes of Fig 2 and 3 may or may not be viable according to the pineapple growth conditions and generalities of the region where production takes place.

The objective of this contribution is to delineate a pineapple biorefinery that eventually adapts to the geographic and cultural conditions of a specific region of Colombia (the Choco-Colombia region), where the pineapple crop is centralized in small farms for local consumption and not in large technical conglomerates, so in many cases the production of fruits does not reach export quality (at least for fresh consumption). This situation is not only characteristic of the Choco-Colombia region, but also occurs in several areas dedicated to the cultivation of pineapples worldwide (Nanda *et al.*, 2012; Singh *et al*., 2016). The differences in the expected quality of the fruit of both production schemes can be deduced from Fig 4.

This document initially presents a description of the main generalities of pineapple cultivation and its market. Then, some of the main products of pineapple and its residues are described. Finally, the peculiarities of pineapple cultivation in the Choco-Colombia region are presented and a possible scenario of pineapple biorefinery for that region is proposed. It is expected that this contribution will become an adequate review material for analysis and decision making in technical and economic feasibility studies to obtain various products from pineapple residues in non-technified crops, for example, in the Choco-Colombia region.

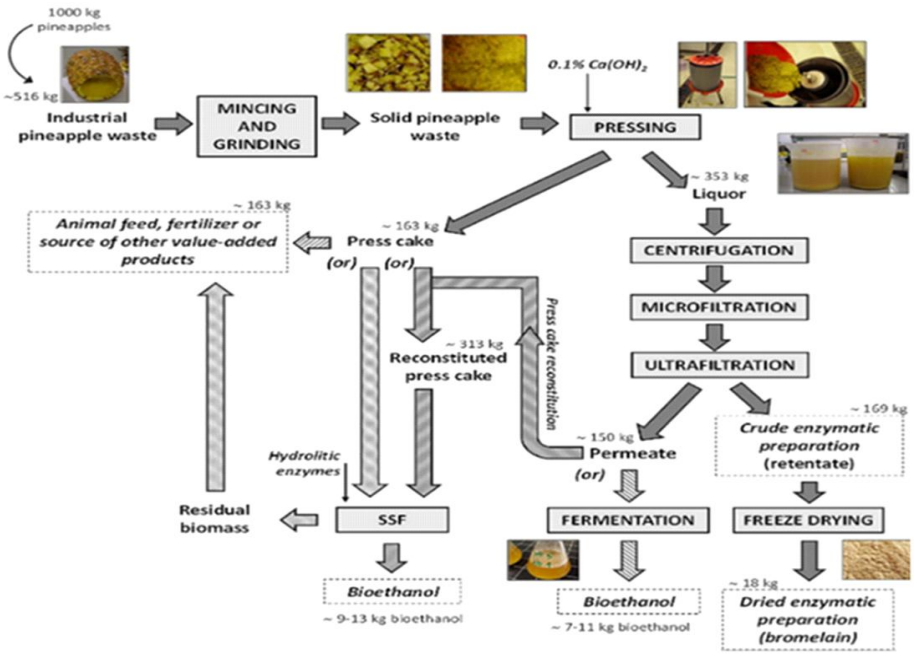


Fig 3: Example of a pineapple bio refinery scheme, taken from (Gil and Maupoey, 2018).

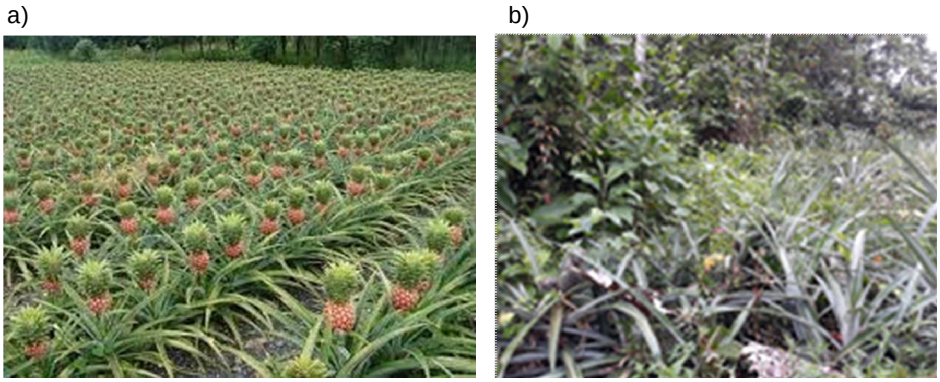


Fig 4: Example of a typical technical pineapple crop (a) and a non-technical pineapple crop in the Choco-Colombia region (b).

Cultivation and commercialization of pineapple

The pineapple is a tropical plant cultivated in a wide range of latitudes (approximately between 30 °N and 30 °S), maximum heights of 800 meters above sea level and it is favored at temperatures between 26°C and 30°C (Sanewski *et al*., 2018). The main producers of the fruit are Costa Rica, Brazil, the Philippines, Thailand, Indonesia, India, Nigeria, China, Mexico and Ghana (Roda and Lambri, 2019). It is estimated that about two thirds of world production is consumed as fresh fruit and the rest is processed industrially, mainly as canned pineapple (~30%) and juice (4%) (Reinhardt and Rodriguez, 2009). In general, pineapple production in countries such as Thailand is concentrated in thousands of small farms; while the production and marketing of pineapple in countries such as the Philippines, Costa Rica, Honduras and Ecuador is represented by large plantation systems with mechanized operations (Sinha *et al*., 2012). In Colombia, despite some efforts and government policies that seek to support and promote the agroindustrialization of products such as pineapple (Lasprilla, 2011), in some regions, such as the Choco-Colombian region, the cultural, demographic, geographic and development characteristics of the region limit the possibility of industrialization, production and commercialization of pineapple. For that reason, the trend remains pineapple production in small non-technical farms and mainly for consumption in local markets.

Vidal-Valverde *et al*. (1982) reported that in pineapple fruits the hemicellulose can reach around the 42% of the cell wall, cellulose around 34%, pectin around 21% and lignin less than 1%. The main sugars present in pineapple fruits are sucrose, fructose and glucose (Finnegan and O'Beirne, 2015; Murcia *et al*., 2020). The soluble solids content in pineapple varies greatly according to maturity, season and cultivation practices (Smith, 1988). Commonly, pineapple maturation is detected by the color change from green to yellow, flat eyes and the well-formed crown. In general, buyers order firmer fruits, with less external color development, with a mass greater than or equal to 1.75 kg and a level of soluble solids content between 12-14% (Smith, 1988; Finnegan and O'Beirne, 2015).

The geographical location of the cultivation areas, cultural practices, post-harvest management practices, equipment and processing operations, as well as the selection of varieties, the season, the degree of maturation and storage conditions can have an effect notorious in the final quality of the product and its shelf life. In general, the climate greatly affects the quality of the fruit, as well as the ripening stage at the time of harvest, the transport conditions and the time between harvest and processing (Finnegan and O'Beirne 2015).

The recommended optimum storage temperature for pineapple is between 7°C and 13°C, while the relative humidity should be between 85-95%. Transportation from growing areas to fresh cut processing plants in major markets can take up to several weeks. Like other horticultural products, physical damage to pineapple can occur along the management chain from harvest to consumption. Physical damage is caused by mechanical factors such as cuts, abrasions, compaction and impact (Paull and Chen, 2014).

Main products from processed pineapple

The processed pineapple includes mainly pulp and juices, among others. The pulp can also be adapted into small pieces and marketed in canned or glass jars (usually in syrup). The quality attributes of the processed pineapple include appearance, color, shape, taste, aroma and nutritional content, as well as texture, product integrity and handling resistance. The shelf life of freshly cut pineapple products is generally between 6 and 15 days at 4-5°C (Montero-Calderón *et al*., 2010; Wu *et al*., 2012).

Pulps

Pineapple pulp is commonly sold in stores in the form of cubes, slices, pieces, wedges or rings. Careful processing and special treatments can help protect the product against moisture loss, juice loss, antioxidants and aroma loss, membrane breakdown and color and appearance changes. Risks of contamination by microorganisms can be reduced by washing the fruits with clean and / or chlorinated water before cutting them (Montero-Calderón *et al*., 2010; Finnegan and O'Beirne 2015). The pulp can be longer

preserved by heat treatment and addition of preservatives. For example, the fresh pineapples cut in plastic bags and sprayed with 15-20% oxygen and 3% argon can be stored up to ten weeks at 1°C (Wu *et al*., 2012).

The pulp from mature pineapple contains on average approximately 85% moisture, 0.70% citric acid and show around 14 °Brix, with a pH of 3.4. It also contains around 6.5-7.0% sucrose, 1.7% glucose and 2.15% fructose. In general, fresh pineapple pulp is a good source of carbohydrates, fiber and minerals, especially Ca, P, Fe, Na and K. It also contains some vitamins, including A, B1, B2, B3, B5, B6, B9 and C. The nutritional content is influenced by several factors that include variety, soil, climatic condition, stage of maturity and management (USDA, 2018).

Dehydrated pineapple

Dehydrated pineapple consists on eliminating most of the free water of the fruit, to obtain a better presentation and to facilitate its management (Chaudhary *et al*., 2019). The final humidity is around 5%, which allows dried fruits to have a longer shelf life. In addition, the powder produced from the husk contained a high total content of dietary fiber (70.6%) similar to that of the apple and citrus fruit, with an insoluble dietary fiber fraction of 99% (Larrauri *et al*., 1997). From the study of Damasceno *et al*., (2016), it was demonstrated that the pineapple peel flour may be a good alternative as a raw material to produce cereal bars. In addition, the biomass of pineapple can serve as a promising prebiotic supplement in dairy products and functional products (Sah *et al*., 2015).

Pineapple juices

In the pineapple processing industries, juice is mainly a byproduct of the process of making slices in syrup and is obtained from the fruit discarded in the process (Reinhardt and Rodriguez, 2009). Generally, pineapple juice is obtained by grinding the fruit and physically separating the solids. Pasteurization is done to prolong its shelf life. The containers can be plastic bottles or bags, coated or multilaminated cans. The yield of pineapple juice can vary between 33% and 56% due to different factors before harvest (including the variety of pineapple, the degree of maturity and the conditions during the growth of the fruit), as well as the factors of processing such as the rate of increase on the pressure during extraction and the duration of the pressing operation, among others (Jaeger *et al*., 2016). The juice is produced naturally and concentrated, the latter from the reduction of its water content by vacuum evaporation or fractional freezing (Linden, 2004). Pineapple juices include those without pulp (clarified or not) and those that contain pulp (purees, pulps and nectars). The fruit juices with pulp are diluted with water and sugar or mixed with syrup or other beverages to achieve the required proportion of sugars / acidity and viscosity (Bhavsagar *et al*., 2010). Nectar is the product of the juice mixture with a certain amount of pulp solids that contain the same amount of °Brix as the original of the fruit (Jaeger *et al*., 2016).

Main products from rejected pineapple and pineapple wastes

Pineapple processing waste, such as the shell, heart and crown, can represent 50% of the weight of the fruit and can generate on average 10 tons of fresh fiber or 1 ton of dry fiber per hectare that are used mainly as animal-supplement food (Sanewski *et al*., 2018). Many studies have been carried out exploring the possibility of giving value to pineapple residues. From there, it has been shown that pineapple processing waste material can be used as a low-cost raw material for industrial processes such as fermentation, extraction of bioactive components, organic acids and enzymatic complexes, among many others (Dev and Ingle, 1982; Tropea *et al*., 2014; Banerjee *et al*., 2018; Gil and Maupoey, 2018; Roda and Lambri, 2019).

Xanthan gum

Xanthan gum is a water-soluble hetero-polysaccharide that is produced industrially from sucrose or glucose by fermenting the gram-negative bacterium *Xanthomas campestris* (Petri, 2015). Xanthan gum has been used in a wide variety of foods due to its emulsion stabilization characteristics and its pseudo plastic rheological properties. It is mainly used in the preparation of salad dressings, bakery products, beverages, prepared foods, soups, sauces, juices and dairy products. Because its thickening properties in aqueous solutions, Xanthan gum is also used as a dispersing agent and suspension stabilizer in pharmaceutical formulations, cosmetics and agricultural products. The effect of production parameters, such as bioreactor operation, type and concentration of nutrients in the growth medium, pH and temperature and so on, are well documented in the literature (Petri, 2015). Amenaghawon *et al*., (2015) obtained yields around 8.48 g/L of Xanthan gum from pineapple peels by means of submerged fermentation processes.

Ethanol

Industrial applications of ethanol include its use in fermented beverages, the food and pharmaceutical industry and its use as an energy product (Idiata and Lyasele, 2014; Tropea *et al*., 2014). In the chemical industry it is used as an antiseptic, dye solvents, resins, soaps, oils, waxes, *etc*. Undoubtedly, the greatest interest in ethanol has been its use as an additive in gasoline or its use as pure fuel, becoming the biofuel with the highest production in the world. In the case of the use of pineapple waste for the production of ethanol, organisms such as *Saccharomyces cerevisiae* and *Zymomonas* have been used. Both organisms are capable of producing approximately 8% ethanol from pineapple residues in 48 h after prior treatment with cellulase and hemicellulase enzymes. (Idiata and Lyasele, 2014; Tropea *et al*., 2014). The *Saccharomyces cerevisiae* strain was used for the continuous production of ethanol from pressed juice of canned pineapple waste (Nigam, 2000). The ethanol production was 92.5% of the theoretical value.

The raw material used was the pineapple canning residue, as well as the fruit juice that was rotted or discarded. The ethanol production was 59.0 g/L without supplementation and pH regulation. Different upgrades to the fermentation technique to produce ethanol from the pineapple and pineapple residues have been also reported (Murcia *et al*., 2020; Upadhyay *et al*., 2013).

Wine

Wine production from pineapple wastes have been studied by means of different techniques and fermentation microorganisms (Santoshkumar and Patil, 2006; Roda *et al*., 2017; Murcia *et al*., 2019). Pineapple wine is a non-vintage wine made from the juice of pineapple, which is typically produced and fermented in similar manner as grape wines. There are detailed studies of the wine production from pineapple using its innate micro-organisms, granulated sugar and baker's yeast in varying proportions (Idise, 2012); or by fermentation under anaerobic conditions (Ibegbulem *et al*., 2014). Typical yields are around 1L of wine/Kg of juice (Roda *et al*., 2017).

Acetic acid and other organic acids

Acetic acid is used as a reactive agent in the production of cellulose acetate and vinyl acetate. It is also used in the pharmaceutical industry for the production of aspirin and in domestic applications as a disinfectant, fungicide, perseverant food and additive in meals. Acetic acid (vinegar) can be obtained by fermentation of pineapple peels through three stages of fermentation. Acetic fermentation, performed on a pilot scale fermenter equipped with an air diffuser flowing sterile air at 34°C, allowed to obtain 50 g/L of acetic acid in 30 days (Roda *et al*., 2016). A complete step-by-step process was arranged to obtain wine and vinegar from the peel and the pineapple core (Roda *et al*., 2016).

By other side, the production of citric acid by fermentation using different species of four species of *Aspergillus* and pineapple residues as substrates have been studied. The higher production of citric acid was between 194.0 and 202.35 g/kg of dried pineapple waste under given specific culture conditions (Tran *et al*., 1988). It has been also reported the use of pineapple syrup for the production of lactic acid using *Lactobacillus lactic* and the enzyme invertase to hydrolyze sucrose into glucose and fructose. Reported yields are around of 20 and 92 g/L (Jin *et al*., 2005).

Bromelain

Bromelain is a glycoprotein that has protease activity commonly used in the food industry. It is used as a meat softener, nutritional supplement and has been used in treatments of digestive disorders, viral diseases and in the formulation of vaccines. Bromelain also has anti-inflammatory, blood clotting and antithrombotic potential (Tochi *et al*., 2008; Gil and Maupoey, 2018). The amount of bromelain in pineapple is about half of the total protein content, being lower the bromelain content in the fruit than in the stem.

Pectin

Pectin is a polysaccharide found in the cell walls of all plants. Pectin is extensively used for the food industry and has been widely used as a thickener, emulsifier and stabilizer, especially in jams, jellies and yogurts. In general, pectin is obtained from the by-products of the manufacture of fruit juices. The extraction of pectin from pineapple residues have been studied (Karim *et al*., 2014). In general, it consists is a multistage physicochemical process involving hydrolysis, extraction and purification processes. Pectin is usually extracted using hot dilute acid (Karim *et al*., 2014). However, these processes are influenced by several factors, mainly temperature (between 60 and 100°C), pH (between 1.5 and 3.0) and time (between 0.5 and 6 hours). The extraction of pectin from pineapple core was carried out with nitric acid and the chemical and rheological properties of the pectin extracted were similar to those of industrial pectin (Conceição *et al*., 2012).

Starch

From a mill process from pineapple waste, in particular from stem, Nakthong *et al*., (2017), obtained high purity starch, with properties compared to rice, corn and cassava ones. Pineapple stem starch, present technical properties as high gelatinization temperature, relatively high amylose content (34.4%), high solubility percentage (more than 32%) and low viscosity under regular cooking conditions. All of these properties confirmed the pineapple starch as a resistant and a thermoplastic starch; thus, multiple food applications of that starch may be considered (Nakthong *et al*., 2017).

Adsorbents

Dyes used in textile industries have been threatened by environmental problems when mixed and dumped with large volumes of wastewater at different stages of the dyeing and finishing processes. The use of pineapple waste has been identified to eliminate dyes. The stem of the pineapple has been used as a low-cost adsorbent to remove the basic dye (methylene blue) from aqueous solutions by adsorption (Hameed *et al*., 2009) In addition, pineapple shell has been effectively used as adsorbent to removing up to 84% of R-40 (typical dye in food industry) and around 60% of typical textile industry dyes from aqueous wastes without any previous treatment. Adsorption capacity was similar to those observed for commercial activated carbon as adsorbent under similar removing conditions (Ardila *et al*., 2018; Urrego *et al*., 2018). Pineapple residues have also been used as an effective bio adsorbent to remove toxic metals such as mercury, lead, cadmium, copper, zinc and nickel from the sludge from contaminated wastewater (Dacera and Babel, 2008).

Fiber

Pineapple leaves have been used to make textiles and thick threads in some Southeast Asian countries (van Tran, 2006). A yield of 2.1 g of fiber/100 g of pineapple pulp waste has been identified. In addition, pineapple leaf fibers are

investigated in the manufacture of fiber reinforced polymer composites due to their high cellulose content, abundance and low cost. It was found that the mechanical properties of the pineapple residues-based compounds are superior to other natural fiber compounds based on cellulose (Arib *et al*., 2006).

Food for animals

Several studies have focused on the exploitation of pineapple residues as ruminant feed. In that sense, the shell, the core of the pineapple and the leaves are being used as food for ruminants (van Tran, 2006). In China, pineapple residues are used as a source of processed foods for milk production (Sruamsiri, 2007).

Source of energy, composting and soil amendment

Pineapple residues are composed of organic substances and, therefore, the problem of elimination could be mitigated by anaerobic digestion and composting. Some of these wastes could have applications for gas production. The biomethanization of fruit waste is the most appropriate waste treatment, since it also provides energy in the form of methane. The pineapple residues were used for the production of methane using a semi-automatic anaerobic digestion that could produce up to 1682 ml/day of biogas with a maximum methane content of 51%. In addition, pineapple residues have been used as a carbon substrate to produce hydrogen gas from municipal sewage sludge (Wang *et al*., 2006). The residue contained carbon and nitrogen source for cell growth and hydrogen production. In addition, research has been carried out on the composting of pineapple waste using earthworms (Mainoo *et al*., 2009). It has been identified that vermicomposting decomposes rapidly, consuming approximately 99% of the pulp of the pineapple of the moist mass, while the shell had a weight loss of almost 87%. The pH of the residue changed from acid to neutral to alkaline during composting.

In another application for pineapple wastes it was found that such wastes can show a positive change when used as soil amendment on growth and yield of species as *Solanum melongena* (Akoijam *et al*., 2018).

Summary of the review

According to the literature review it is clear that pineapple wastes contain many high-value reusable substances. Therefore, pineapple processing by-products and rejected fruits that pollute the environment could become products with added economic value. As previous shown, different schemes for a pineapple biorefinery can be developed. Fig 5 summarizes a rational scheme of pineapple biorefinery according to the literature review. However, not all processes or products derived from pineapple wastes are suitable to be obtained according to the specific conditions of the harvest area.

A possible pineapple biorefinery in the Choco-Colombia region

In the Choco-Colombia region, two varieties of pineapple are recognized: one of them is known locally as “tabugana pineapple”, which is characterized by being rounded, with pronounced and rounded eyes, without thorns and a high content of water. It has an average length and width of 20.5 cm and 15 cm, respectively. The other variety is known as “chocoana pineapple”, this fruit is elongated, with angular eyes, it has thorns and is sweet. The average length and width are 19 cm and 11.2 cm, respectively (Murcia, 2013). Both pineapple varieties are cultivated by the afro-descendants and native communities of the region. All the production of pineapple in the Choco-Colombia region is grown on a small scale, in farms between 1 and 5 hectares. Notwithstanding, pineapple cultivated area in the Choco-Colombia region presented a significate increase in last years, passing from 2,700 tons in 2007 (with a cultivated

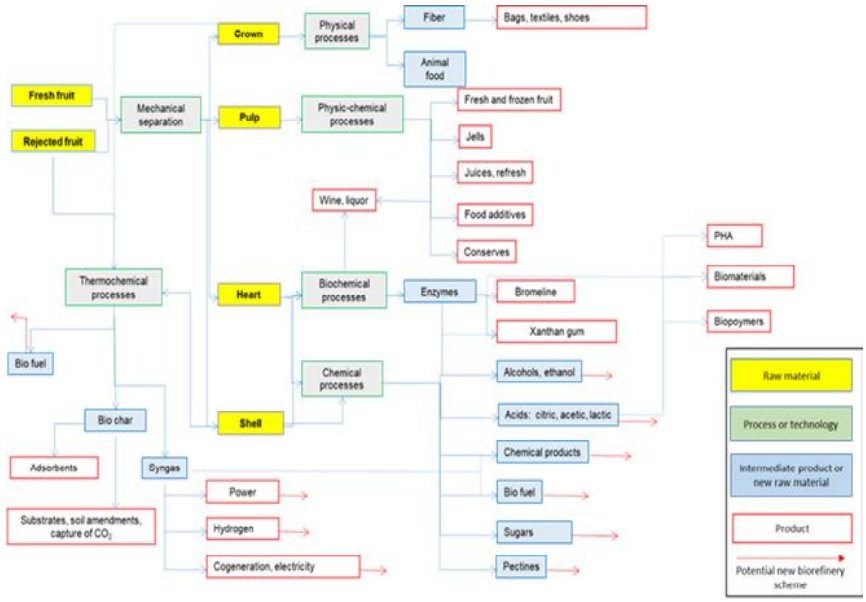


Fig 5: A general biorefinery scheme for pineapple and pineapple wastes according to the literature review.

area closer to 120 hectares) to a production above 8,000 tons in 2016 (with a cultivated area higher than 400 hectares) (MADR, 2019; Murcia *et al*., 2019). Unfortunately, due to the specific climatological, social and cultural conditions of the region (which actually corresponds to one of the most poverty regions in Colombia), plus to the lack of technician conditions for the pineapple harvesting, the proportion of rejected fruit is closer to 50%. Therefore, the increase in pineapple production in the Choco-Colombia region is linked to the massive generation of waste, which is generally discharged without obtaining any value-added products. Consequently, small producers are negatively affected in their profitability. In this order of ideas, due to the relative huge amount of pineapple biomass generated and discharged to the environment without proper treatment, serious environmental impacts occur. To reduce these pollutants, the sustainable conversion of these into value-added products is of extreme importance.

In Chocó, the pineapple harvest is manual and is usually done before ripening. Pineapples are collected and put in boats to be transported by the river to the centers of commerce and consumption. The main problems that deteriorate pineapple quality are damage due to impacts on loading, transportation, unloading and storage. Transport does not require refrigeration if the travel time is less than 2 days, however, the quality of the fruit is preserved and improved if refrigerated after harvest. Fruits should be refrigerated at a temperature between 7°C and 10°C if they are going to be transported more than 3 days (Sanewski *et al*., 2018). This is a problem in the Choco-Colombia region, where temperatures reach values between 20 and 37°C and the means of transport generally do not allow refrigeration, so the fruit commonly deteriorates in less than 5 days. Transport and commercialization conditions (Fig 6) make it easier to increase the number of rejected pineapples. During the trip the pineapples are exposed to mechanical damages and during their commercialization they could be attacked by plagues like the fly.

According to the review of the literature and given the relatively high amount of pineapple rejected in the region, the recovery of pineapple waste can improve the economy of the region and reduce the negative environmental impact of waste disposal. Due to poverty and the relative economic backwardness in the region, the process technology to be selected must be fairly simple, relatively cheap and easy to install and operate. In addition, the target products must correspond to those of the established market, the market of high potential, the long service life and with easy transport or direct consumption in the same region.

In Fig 7, a pineapple biorefinery is proposed for the Choco-Colombia region. Despite the multiple processes that could be implemented and the multiple products that could



Fig 6: Typical transport and commercialization of pineapple in Choco-Colombia region, taken from (Murcia, 2013).

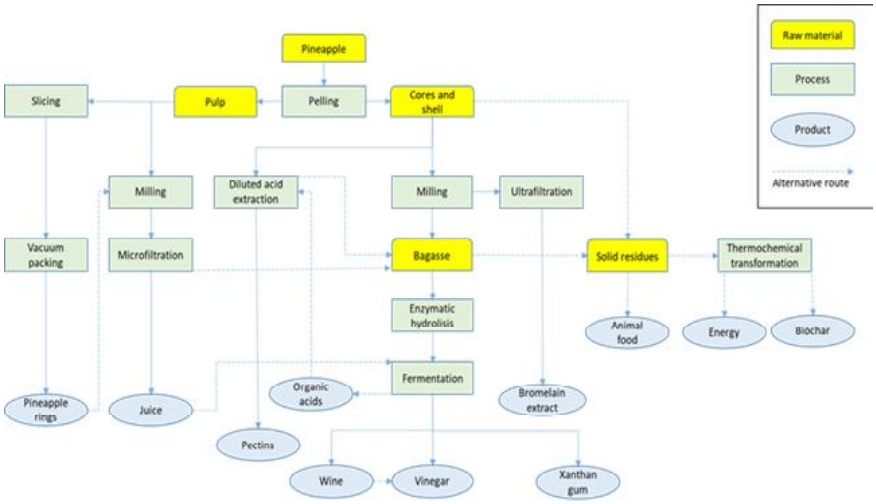


Fig 7: Pineapple biorefinery proposal for the Choco-Colombian region.

be obtained, the proposed biorefinery focuses on those that could be relatively easy to obtain according to the development of the region. The rejected pineapple must gather and peel mechanically to separate the pulp, the core and the peel. The process can be carried out as a manual operation given the high availability of unskilled labor in the region, becoming a new employment alternative for local inhabitants. The pulp can be processed to obtain pineapple rings and juices for sale in the region and in other Colombian regions. Pineapple rings should be vacuum packed to prolong their shelf life. The core and shell are intended for pectin extraction, bromelain extraction and fermentation processes. Pectin and bromelain are selected as target products because they are high demand products in different Colombian industries, which favors their commercialization. By fermentation, wine and vinegar could be the most important target products because they are products of relatively high demand in the same region. Xanthan gum is included due to its high added value and high demand in national and international markets. By fermentation it will also be possible to obtain organic acids that could be sent to local markets or used as raw material in the same biorefinery, *i.e*., for the pectin extraction process. The production of ethanol through the fermentation of pineapple residues is not considered because the trend technologies in the country favor the use of more extensive crops, such as African palm or sugarcane. Therefore, the availability of pineapple waste in the region may become insufficient for competitive commercial production of ethanol.

As an alternative process, instead of the biochemical fermentation process, all solid waste can be used for the preparation of animal feed supplements or as a raw material for thermochemical transformations (*i.e*. gasification or pyrolysis). Through the thermochemical transformations, the main expected products are energy (which can be used in other process transformations in the same biorefinery) and the biochar that can be used as soil amendment in the small pineapple farms or as adsorbent for water pollutants generated in other economic activities from the region, for example, heavy metals mining.

CONCLUSION

This review is of particular importance for the pineapple sector in the Choco-Colombia region and for pineapple growing areas with the same characteristics throughout the world. Adding value to pineapple will also provide diversification, which allows an additional source of income for the pineapple sector and reduces the market risk associated with the pineapple trade.

Economic and environmental sustainability is achieved through the optimal use of renewable raw materials and there is a need for a process engineering approach to ensure maximum economic and social benefit through minimization of the use of material and energy resources. Pineapple wastes contain many high-value reusable substances. The industrial applicability for the extraction or production of substances such as bromelain or pectins (among others) under a biorefinery scheme has not been previously studied in the region; therefore, it could become a new opportunity for business and industrial development.

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