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Redefining Waste: Apple Pomace as a Resource for a Sustainable Food System

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Abstract

Apple pomace a byproduct generated from the processing of apples into various food products. This fibrous residue consists of peels, cores, and seeds left after extraction of the primary juices and has traditionally been considered waste. However, in recent years, apple pomace has gained attention due to its rich composition of valuable nutrients, including dietary fiber, phenolic compounds, vitamins, and minerals. Research into apple pomace has focused on its potential applications in various industries, particularly in food, pharmaceuticals, and agriculture. It has been explored as a source of dietary fiber for functional foods, antioxidants for nutraceuticals, and bioactive compounds for pharmaceutical formulations. Additionally, apple pomace shows promise as a feedstock for biofuel production and as a source of pectin and polyphenols used in food processing and preservation. These pathways include production of biochemical (lactic acid, biobutanol, bioethanol, bio-succinic acid, acetic acid, pectin), functional foods (apple pomace enriched rice blends, bread, snacks, noodles), dermal formulations (quercetin-based) and bio based polymers (polyhydroxyalkanoates (PHA)). In this context, apple pomace bio refineries must be constructed to achieve total waste utilization

wherein lifecycle assessment (LCA)studies should be implemented. Efforts to valorize apple pomace align with sustainability goals by reducing waste and maximizing resource efficiency in the food industry.

Keywords: Apple pomace, Dietary fiber, Health, Antioxidants, Functional foods valorization

Introduction

Apples are widely regarded as one of the most popular and frequently consumed fruits, valued for their perceived health benefits. They are consistently available year-round. Approximately one-third of the overall production undergoes processing to yield a diverse array of products, spanning from juices, vinegars, and both alcoholic and non-alcoholic beverages to chutneys, canned goods, as well as dried and frozen products (Skinner et al., 2018). The processing inevitably leads to the generation of waste (25%) of the apple mass called pomace comprising of its peels, seeds, and fibrous pulp which is discarded. It can be fermented easily thereby poses challenge to environment. The disposal of apple pomace entails significant financial implications, prompting a growing interest in exploring its commercial applications. Recently, apple pomace has been leveraged for various purposes, including incorporation into animal feed for fiber and polyphenol extraction for use in Nutraceutical or dietary supplements (Lu and Foo, 1997; Kennedy et al., 1999; García et al., 2013; Bai et al., 2013), as well as inclusion in various food products. Apple pomace is a store house of valuable compounds. It is rich in protein, fats, carbohydrates and minerals. It contains 2.7%-5.3% protein and 1.1%-3.6%fat, which is much more than that of apple (Kennedy et al., 1999).Carbohydrate content is also very abundant in apple pomace with simple carbohydrates comprising mainly of fructose (44.7%) and glucose (18.1%-18.3%). As far as complex carbohydrates are concerned, its percentage is also high in apple pomace as compared to apple. Complex carbohydrates primarily comprise of insoluble fiber (33.8%–60.0%), soluble fiber (13.5%-14.6%) and pectin (3.2%-13.3%) (Table 1). Major minerals reported in apple pomace are sodium (185.3mg/100g), potassium (398.4–880.2mg/100g), calcium (55.6 – 92.7 mg/ 100g), phosphorus (64.9 – 70.4 mg/100g) andmagnesium (18.5 – 333.5 mg/100g). Trace elements present are iron (2.9%-3.5%), zinc (1.4%), copper (0.1%) and manganese (0.4% - 0.8%). Moreover, the world is shifting from linear economy to a circular bio economy (Taherzadeh, 2019) and this cannotbe achieved without the waste valorization of one the world'smost consumed fruit. Effective disposal of apple pomace has been a global problem (Pachapur et al., 2015) since a long time now because of the huge cost involved and the amount of green house gas emissions released into the environment (Lin et al., 2013). Taking into account the vast amount of apple pomace generated every year, one cannot rely only on "food and feed utilization "of apple pomace (Fang et al., 2021). The countries must now look beyond this. Extensive bio refineries (Magyar et al., 2016) must be constructed where in multiple pathways should be developed for apple pomace utilization. Novel approaches for sustainable usage of apple pomace should be looked into which comprise of biochemical production or dermal formulation formation or even bioplastics can be produced by linking apple pomace bio refineries of plastic production units. In order to have a sustainable economy, life cycle assessment (LCA) studies (González-García et al., 2018) must be conducted from time to time thus judging the overall apple pomace valorization process.

Table 1: Proximate composition of apple pomace

Composition (%)	Apple pomace (dry basis)	References
Moisture	4.4 – 10.5	(Dourado et al., 2022; Mandelblatt et al., 2020; Harris et al., 2012; Forrest et al., 2007; Chen and Lahaye, 2021)
Protein	1.2 – 4.7	
Lipids	0.6 – 4.2	
Total Dietary Fiber	14.5 – 26.5	
Ash	1.5 – 2.5	
Carbohydrates	45.1 – 83.8	

Nutritional Composition

Diets characterized by low dietary fat intake have shown preventive effects against various degenerative conditions such as diabetes, obesity, cardiovascular disease (CVD), and certain cancers. An average apple contains approximately 0.16%–0.18% fat, whereas apple pomace exhibits a higher fat content ranging from 1.1%–3.6%. Notably, apple pomace, which includes seeds, is particularly abundant in fatty acids, notably linoleic acid (18:2 n-6) and oleic acid (18:1 n-9) (Bhushan et al., 2008). Linoleic acid, an essential fatty acid, is associated with potential benefits such as reducing the risk of atherosclerosis, improving impaired glucose tolerance, and mitigating body fat accumulation. However, due to its relatively modest fat content, apple pomace is not considered a substantial source of these fatty acids. Furthermore, while apples are not renowned for their protein content, apple pomace typically contains higher levels of protein, likely attributable to the inclusion of seeds. Carbohydrates constitute approximately 14% of the nutrient composition of apples, with apple pomace exhibiting a higher carbohydrate content compared to whole apples (USDA, 2016). The sucrose content in apple pomace may vary considerably among different cultivars, and both apples and apple pomace contain notable quantities of fructose and glucose. The higher levels of fructose and glucose in apple pomace are attributed to the presence of sugar containing acids and seeds. Among commonly consumed fruits, apples have relatively higher fructose concentration (Bhushan et al., 2008).

Free fructose, poorly absorbed in the small intestine, thereby escapes absorption and undergoes fermentation in the large intestines. Apples also contain complex carbohydrates like polysaccharides. Chen et al. (2017), supplemented male Kunming mice with high-fat diet (HFD; 45% fat content and served as control group) and HFD along with apple pomace polysaccharides at doses of 200-800 mg/kg b.w/day for 30 days (Test group). Results indicated that all doses of apple pomace polysaccharides improved serum lipid profile, insulin, and adiponectin levels compared to control counterparts. Supplementation with 200 mg/kg b.w./day of apple pomace polysaccharides also reduced serum leptin levels and all doses increased antioxidant capacity, serum hexokinase and glucagon concentrations, indicating a restoration of metabolic balance. The results indicate that supplementation with apple pomace polysaccharides have a potential in treatment for metabolic or obesity-related diseases.

Dietary fiber, an essential component of a healthy diet is recommended to be consumed for various health benefits. Among the commonly consumed fruits, apples with skin are recognized for their notably high dietary fiber content. Given that apple pomace comprises not only the flesh but also the skin, stem, seeds, and calyx, it generally exhibits a higher fiber content compared to whole apples. Reports suggest that apple pomace contains 4.4–47.3 g of fiber per 100 g, with variability attributed to different apple cultivars and fiber quantification methods (Bhushan et al., 2008). Apple pomace contains a substantial amount of insoluble fiber, predominantly cellulose and lignin, along with soluble fiber, primarily pectin. Due to its elevated fiber content, consuming 100 g of apple pomace can supply approximately half of an individual's recommended daily fiber intake. Increased dietary fiber intake has been linked to gastrointestinal health advantages and a diminished risk of diverticular diseases and specific cancers, notably colorectal cancer (Bradbury et al., 2014).

Studies investigating fiber-rich colloids extracted from apple pomace have demonstrated increased microflora fermentation, higher levels of short-chain fatty acids (SCFAs) in the cecum, and increased bile acid excretion in faeces in animal models. Furthermore, supplementation with fiber-rich colloids from apple pomace has led to reduced weight gain and improved lipid profiles, with decreased serum total cholesterol and LDL-C levels, and increased HDL-C levels (Sembries et al., 2006). Pectin, the main fiber constituent in apple pomace, has been shown to inhibit pancreatic lipase, suggesting a potential role in reducing fat absorption and caloric intake, thereby potentially aiding in weight management (Kumar and Chauhan, 2010).Overall, apple pomace, rich in dietary fiber and polysaccharides, holds promise as a functional food ingredient with potential health benefits, particularly in promoting gastrointestinal health, reducing the risk of chronic diseases, and aiding in weight management. Further research, including clinical trials is necessary to fully elucidate the health effects of apple pomace consumption and its potential role in disease prevention and management.

Minerals play a crucial role in maintaining overall health. Potassium, abundant in fruits and vegetables, is known to lower blood pressure. Apples contain 107 ± 2.21 mg per 100 g of fresh weight potassium while apple pomace has higher potassium content 639.36 per 100 g of fresh weight (Koutsos et al., 2015). Similarly, calcium and phosphorus are vital for bone health, with adequate intake associated with a reduced risk of osteoporosis. While oranges are a richer source of calcium compared to apples, apple pomace contains more calcium per 100 g than oranges. Additionally, apple pomace is richer in phosphorus compared to whole apples, making it a valuable source of this mineral. The mechanisms underlying the improvement of bone health by fruits and vegetables, including the acid-base hypothesis, suggest that alkaline precursors such as potassium, calcium, and magnesium in these foods neutralize the acidic effects of low pH foods, thereby potentially reducing bone resorption and maintaining bone density. Furthermore, in terms of iron and zinc, apple pomace exceeds whole apples in their content. Iron deficiency anaemia represents a prevalent global health concern, and whole fruits are typically not good source of iron. However, apple pomace contains elevated levels of iron compared to whole apples (Bhushanet al., 2008). Similarly, zinc deficiency is prevalent, and apple pomace provides higher amounts of zinc compared to whole apples (Wessells and Brown, 2012). The inclusion of apple peels, known to be richer in several minerals including sodium, potassium, calcium, magnesium, and iron, contributes to the higher mineral content in apple pomace. These findings suggest that apple pomace could serve as a valuable dietary supplement to enhance mineral intake.

Vitamins C and E act as potent antioxidants, scavenging reactive oxygen species and offering protection against oxidative stress-related diseases. Though are poor source level of vitamin C

(0.057 mg/g) compared to other widely consumed fruits, exhibit notable antioxidant activity (97.23 mmol of vitamin C equivalents/g). Regarding the collective antioxidant activity contributed by vitamin C, apples rank second only to cranberries (176.98 mmol of vitamin C equivalents/g). Apple pomace, containing approximately 22.4 mg of vitamin C per 100 g, serves as another potential source of antioxidant compounds. Vitamin E, abundant in seeds, is also present in apple pomace, further contributing to its antioxidant properties (GarciaClosas et al., 2004). Overall, the nutritional composition of apple pomace underscores its potential as a functional food ingredient rich in essential minerals, vitamins, and phytochemicals with antioxidant properties, warranting further exploration for its dietary and health-promoting applications.

Health Benefits

Antioxidant Potential

Apples are rich in polyphenolic compounds, including flavanols, flavonols, hydroxyl cinnamates, dihydrochalcones, and anthocyanins. Popular varieties such as Fuji, Red Delicious, and Gala are particularly high in phenolics and flavonoids, contributing to their antioxidant properties. Even during fruit processing, which may modify nutrient composition, apple pomace retains abundant levels of polyphenolic antioxidants. These antioxidants persist in the pomace post-processing, as they are primarily concentrated in the skin. Polyphenolic compounds present in apple pomace, including catechin, p-coumaric acid, caffeic acid, and ferulic acid, exhibit robust scavenging abilities against free radicals, exceeding the antioxidant capacities of vitamins E and C. Apple pomace is also rich in antioxidants such as phloridzin, chlorogenic acid, epicatechin, quercetin etc, with excellent radical scavenging activities (Lu and Foo, 1997). Extensive studies have been conducted to highlight the affluent polyphenols present in apple pomace along with their outstanding radical scavenging characteristics (Kennedy et al., 1999). For instance, (Lu and Foo, 1997) reported that DPPH-scavenging activity of apple polyphenols was 2-3 times and superoxide-scavenging activity was10-30 times to that of vitamin C (0.35 EC_{50}) or E (0.30 EC_{50}). Furthermore, in a study conducted by Garcia et al., 2013, apple pomaces from eleven different apple varieties were examined for antioxidant activity where in DPPH (2, 2 – diphenyl-1-picryl-hydrazyl-hydrate) and FRAP (ferric ion antioxidant reducing power) was conducted and found that DPPH and FRAP values were 4.4 and 16.0 ascorbic acid per kg of dry matter which clearly exhibited that apple pomace is a rich source of antioxidants (Garcia et al., 2013). Antioxidant activity of eight phenolic compounds (Bai et al., 2013), discovered in industrial apple pomace have been enlisted in the

Table 2. Quercetin and its glucosides, abundant in apple pomace, have been associated with the prevention of cardiovascular disease and cancer (Boyer and Liu, 2004). Studies have shown that polyphenols isolated from apple pomace exhibit superior antioxidant activities compared to vitamins C and E, emphasizing the potency of apple pomace as a source of dietary antioxidants (Bhushan et al., 2008).

Table 2 Antioxidant profile of apple pomace

Phenolic compounds	Apple pomace (mg/kg dry matter)	References
Catechin	2400	
Epicatechin	161 - 9300	(Kaur and Das, 2011;
Caffeic acid	10.5 - 280	Mitsuoka, 2014; Arai,
3-Hydroxyphloridzin	270	1996; Saher et al., 2004;
Chlorogenic acid	393.2 – 14,300	Lyu et al., 2020)
Phloretin xyloglucoside	82.9 - 170	
Phloridzin	587.2 – 11,400	
Quercetin-3- galactoside	224.2 - 1610	
Procyanidin B-2	329.1 - 9300	
Quercetin- 3- glucoside	27.6 - 3900	

Cardiovascular diseases

Ravn-Haren et al., 2013 investigated the impact of apple pomace consumption on plasma lipid profiles in healthy individuals. Participants consumed apple pomace (22 mg/d), apples (550 g/d), fiber rich apple juice (500 mL/d) and clear apple juice (500 mL/d) as part of a randomized crossover study. The results showed that apple pomace consumption did not significantly affect serum cholesterol levels compared to other forms of apple consumption, possibly due to lower pectin content. However, there was a trend towards decreased heart rate, blood pressure, and certain markers of inflammation and insulin-like growth factor, suggesting potential cardiovascular benefits. Additionally, apple pomace consumption improved gastrointestinal health, indicated by reduced lithocholic acid excretion. Rago et al., 2015 using untargeted metabolomics revealed that apple pomace consumption positively impacted insulin sensitivity and gut microbial function. It led to decreased levels of aromatic amino acids associated with gut fermentation and insulin resistance. Moreover, apple pomace reduced plasma acylcarnitines and bile acids linked to cholesterol metabolism. However, it increased plasma uric acid levels, warranting further investigation due to its association with metabolic disorders and cardiovascular risk. Studies in animal models have shown promising effects of apple pomace on body weight and lipid metabolism. Cho et al.,2013 fed rats a high-fat diet (HFD) supplemented with apple pomace and observed reduced body weight, body fat percentage, and improved serum lipid profiles, including lower LDL-C and higher HDL-C levels. This was attributed to altered lipid metabolism, as evidenced by reduced liver cholesterol and triglyceride content. Bobek et al., 1998 reported similar findings in rats fed a cholesterol-rich diet supplemented with apple pomace. They observed reduced liver cholesterol content, decreased activity of cholesterol-synthesizing enzymes, and improved antioxidant enzyme activity. These effects were attributed to the fiber content of apple pomace, which binds to bile acids and promotes their excretion. The lipid metabolism was also evaluated by Macagnan et al.,2015,who demonstrated that feeding of apple pomace (68.8g/kg) for a period of 34 days to weanling rats resulted in highest percentage of faecal lipids and reduced serum TAG and hepatic LDL-c.

Gastrointestinal Health

The beneficial effects on gastrointestinal (GIT) health were also evaluated by determining gastrointestinal biomarkers and digestibility (nitrogen intake- nitrogen in faecal excreta and urine). Processed and unprocessed apple pomace supplementation decreased the gut enzymatic activity (β -glucuronidase and β -glucosidase) thereby improving GIT health without effecting nitrogen utilization. Additionally, unprocessed apple pomace favorably modified antioxidant status. Likewise, Kosmala et al., 2011 studied the effect of supplementation of apple pomace 0.23%w/w; decreased flavonoid 0.10%w/w and flavonoid depleted 0.01% w/w along with standard rat diet on gastrointestinal health in male wistar strain for 4 weeks. Rats fed on all apple pomace groups showed increased intestinal fermentation and SCFA production, improved gut enzyme activity, and decreased fecal pH. Furthermore, significant increase in cecum weight was observed in rats fed on 0.23%w/w pointing towards greater potential to metabolize high energy foods additionally, the rats exhibited decreased activity β-glucuronidase thereby decreasing the risk of colon cancer. Thus the flavonoids and fiber present in apple pomace promoted fermentation and improved gut microbiota hence GIT health.

Glucose Regulation and Insulin Sensitivity

Apple pomace supplementation has shown promising results in improving glucose regulation and insulin sensitivity. Animal studies have demonstrated reduced fasting glucose and insulin levels, improved insulin resistance, and modulation of key proteins involved in glucose and lipid metabolism. These effects were attributed to the fiber and polyphenol content of apple pomace, which may enhance insulin sensitivity and glucose uptake. Studies have shown that supplementing animal diets with apple pomace decreased blood glucose levels (Juśkiewicz et al., 2011; Kosmala et al., 2011). Another study conducted by Maet al.,2016 illustrated that apple pomace (500mg/kg) and rosemary extract to rats improved fructose induced plasma and adipose insulin resistance, HOMA-IR by attenuating CD36 cells and the GLUT-4 transporter.

Food Applications

Apple pomace is widely incorporated into food products to enhance their nutritional content and appeal to consumers. Its versatility extends to various culinary applications, where it serves as a functional ingredient. For example, the addition of apple pomace to bakery items, confectionery, dairy products, and meat dishes has proven to enhance their nutritional value, introduce pharmacological benefits, increase phytochemical content, and promote overall health.

Baked Products

Marilisa et al., 2018 developed short dough biscuits by incorporating apple pomace at 10% and 20% and revealed that the substitution of wheat flour at both the levels reduced the glycaemic index to 65 and 60 in comparison to control (70, without apple pomace). In a study by Usman et al., 2020, it was observed that incorporating 10% apple pomace powder into wheat flour resulted in the production of cookies with enhanced organoleptic attributes, as determined by sensory evaluations and compositional analyses. Moreover, the addition of increasing quantities of apple pomace, up to 30%, to baked scones and extruded snacks did not significantly alter the proximate composition of the final products, with the exception of starch and fiber content in baked scones. Products with higher levels of fiber, phenolic content, and antioxidant capacity were observed when apple pomace was included at this level (Reis et al., 2014).

Prior research indicates that incorporating 3% apple pomace into bread leads to decreased stiffness and delays the onset of staleness (Jannati et al., 2018). Moreover, apple pomace has been utilized in various applications to enhance the flavor and nutritional profiles of cakes and other bakery items (Sudha et al., 2007). The addition of apple pomace to wheat flour improves dough viscosity, although it reduces uniaxial extensibility. Additionally, integrating apple pomace into cookies has been demonstrated to reduce their glycemic index (Marilisa et al., 2018).

Fortified bakery items containing apple pomace exhibit notably elevated dietary fiber content, with fortified cookies demonstrating softer, chewier textures and garnering more favorable consumer reception (Jung et al., 2014). On an industrial scale, apple pomace flour, rich in flavonoids, total polyphenols, and dietary fibers, has been developed and evaluated for various characteristics. Substituting wheat flour with 25%, 50%, or 75% apple pomace flour in cookies yielded products that maintained their health-enhancing constituents, fruity aroma, and crisp texture even after one year of storage (Zlatanović et al., 2019).

Moreover, fortified bakery items containing apple pomace have demonstrated DNA/cytoprotective attributes, suggesting their potential as functional foods enriched with phytochemicals (Sudha et al., 2016). Therefore, the utilization of apple pomace in bakery foods not only facilitates the production of phytochemical-enriched functional foods but also contributes to the sustainable management of waste pomace.

Confectionary and Snack Items

Apple pomace has the potential to undergo bio transformation by basidiomycetes into complex and flavorful combinations suitable for the confectionary industry (Bosse et al., 2013). In a separate study investigating the use of fruit pomace, particularly apple pomace, as an ingredient in shortbread cookies, it was found that cookies enhanced with apple pomace exhibited superior sensory qualities compared to those baked using a regular recipe. These fruit pomace-infused cookies not only stood out in terms of taste but also boasted health-promoting qualities, giving them a competitive advantage in the market (Radzyminska et al., 2017).

Moreover, jams made from apple pomace were discovered to be abundant in phenolic compounds, carotenoids, dietary fiber, and antioxidant activity (Kapoor et al., 2023). Despite originating as a byproduct of juice processing, apple pomace is endowed with valuable bioactive compounds including phytochemicals, antioxidants, and dietary fiber, albeit posing potential environmental ramifications. Research has shown that noodles incorporating apple pomace exhibit elevated levels of protein, total dietary fiber, and antioxidant activity (Yadav, and Gupta, 2015). These findings collectively suggest that apple pomace can be effectively utilized in confectionary to enhance their nutritional, functional, and commercial value.

Dairy Products

Apple pomace has been employed in diverse dairy products to augment their characteristics and nutritional profile. In yoghurt, apple pomace serves as a natural preservative and texturizer (Wang et al., 2000). The quantity and concentration of apple pomace, ranging from 0.1% to 1%, play a crucial role in the creation of skim milk and certain fermented products (Wang et al., 2000). Incorporating 1% apple pomace in yogurt production not only shortens the fermentation process but also increases the gelation's pH. Moreover, studies have shown that adding apple pomace powder to fiber-fortified yogurt can affect acidity and increase the amount of total soluble solids. Additionally, apple fiber enhances sensory characteristics such as color, texture consistency, and flavor. Acidophilus yogurt enriched with apple pomace up to 10% has been successfully developed without compromising quality (Issar et al., 2017).

Furthermore, dairy products like "burfi" fortified with apple pomace have been found to be more nutritious compared to conventional ones in various trials (Tanuja et al., 2017). In accordance with the rising interest in functional foods aligned with sustainable development goals, a new probiotic yogurt enriched with 1%, 3%, and 5% apple pomace flour has been formulated. Among these formulations, the yogurt fortified with 3% apple pomace flour demonstrated optimal attributes including hardness, cohesiveness, viscosity index, color, and taste scores, indicating its suitability for producing distinctive and advantageous yogurt products (Jovanović et al., 2020).

Meat Products

The development of meat patties, apple pomace was incorporated at levels ranging from 2% to 8% of buffalo meat, depending on the source. Increasing the inclusion of apple pomace powder resulted in improvement in water holding capacity, cooking yield, and meat emulsion stability. Post-cooking, there was a decrease in the pH of the patties, accompanied by increases in their moisture content, water activity, fat content, and crude fiber content. Furthermore, the textural attributes of the patties, including firmness, toughness, and hardness, were improved (Younis and Ahmad, 2018).

Moreover, scientific investigations indicate that the utilization of pomace fiber extract serves as a fat substitute to enhance the rheological characteristics of meat preparations and stabilize emulsions (Choi et al., 2009). In controlled experiments, sausages were manufactured by incorporating apple pomace fiber at 1% or 2%, thereby substituting pork fat at 5% or 10% (Choi et al., 2016). Chicken sausages, exhibiting excellent acceptability, heightened dietary fiber content, and improved shelf stability for up to 15 days at ambient temperature, were formulated through the addition of dried apple pomace powder at a concentration of 6%(Yadav et al., 2016a).

Impingement drying emerged as a rapid and efficient method for producing dried apple pomace powder, characterized by a high retention of bioactive constituents. Meat products fortified with apple pomace displayed elevated levels of dietary fiber and radical scavenging activity compared to the control group (Jung et al., 2015). Furthermore, a comprehensive physico-chemical, textural, and sensory assessment of apple pomace powder as a fat substitute in reduced-fat goshtaba formulations revealed generally favorable palatability when apple pomace powder was incorporated at concentrations ranging from 1% to 3% (Rather et al., 2015). Proximate analysis of apple pomace unveiled a protein content of 4.50% and a total dietary fiber value of 62.67%. It demonstrated a notable capacity for water and oil retention, along with effective antibacterial properties against various bacterial infections. Sausages prepared from buffalo meat and apple pomace powder exhibited high cooking yield and stable emulsion, with an anticipated elevation in dietary fiber content (Younis et al., 2015).Consequently, the incorporation of apple pomace in diverse forms into various meat products holds promise for augmenting their dietary fiber and other bioactive constituents, thereby bolstering their nutritional profile and health-enhancing attributes.

Apple Pomace Valorization Routes

Apple pomace, due to its high nutritional and antioxidant content, presents an array of options for valorization. The major ones being used as biochemical agents (lacticacid, biobutanol, bioethanol, biosuccinic acid, acetic acid, pectin) for production, functional food preparation, cosmetic product manufacture and bioplastic production. These valorization routes have been discussed in detail in the subsequent paragraphs.

Biochemicals/Biomolecules

Lactic acid can be produced using apple pomace through the process of simultaneous saccharification and fermentation (SSF)" (Alonso et al., 2009). Sequential hydrolysis and fermentation can also be used to produce lactic acid using apple pomace (Gullón et al., 2008). It is utilized immensely in foodsector, medicine industry, fabric making, tanneries and synthetic industry (John et al., 2009). Furthermore, it serves as a starting material for the production of poly lactic acid (PLA) (Sembries et al., 2006) which in turn is very much in demand in the biomedical industry due to its structural advantages and environment friendly nature (Adsul et al., 2007). Lactic acid impacts the anabolic and catabolic functions of the cell by acting as an energy providing medium (Saini et al., 2016) for them. In addition to this, it can easily pass through the cell membrane as it has no charge and a minute size (Philp et al., 2005). Last but not the least, it safeguards the cell from unwanted radicals that are produced during the cell circuit on thus show casing free radical scavenging characteristics (Lampe et al., 2009).

Biobutanol and bio ethanol can also be produced using apple pomace through the process of fermentation. Alcoholic fermentation or acetone-butanol-ethanol (ABE) fermentation must have been employed to produce these two chemicals. A very important step before the fermentation of apple pomace is that of pretreatment (Molinuevo-Salces et al., 2020). The proper pretreatment ensures that simple sugars are removed from the substrate i.e. apple pomace and the procured hydrolysate is now mainly composed of hexose and pentose sugars. The biggest drawback of the pretreatment process is that it can sometimes give rise to harmful contaminants which can in turn stop the fermentation process. This is because not all microbial strains are capable of properly fermenting diverse variety of sugars present in lingo cellulosic hydrolysates. Thus, it is of utmost significance to select a proper strain that can treat lingo cellulosic hydrolysates. In case of alcoholic fermentation, *Saccharomyces cerevisiae* is traditionally used. In case of ABE fermentation, *Clostridium beijerinckii* is being employed for apple pomace valorization. One very refreshing approach in the bio butanol and bioethanol production from apple pomace is the utilization of exhausted fermentation broths formed than production. This approach promotes sustainability to a whole new extent as it involves valorization of the complete waste. The exhausted fermentation broths can be subjected to the process of anaerobic digestion thus providing a sustainable way for utilizing the fermentation by-products. Furthermore, anaerobic co-digestion can be employed where in apple pomace along with any livestock manure can be used for methane production (Molinuevo-Salces et al., 2020).

Biobutanol can be used as a constituent of aviation fuel as well as diesel fuel as this helps to minimize carbon dioxide discharge into the environment (Dzięgielewski et al., 2014). It has beenfound that when used as an aviation fuel, bio butanol helps to eliminate common problems of excess vapour pressure and high adsorptivity associated with bio ethanol usage (Chisti, 2008). Eco friendly traits like lowering down of nitric oxide gases and smoke discharges as well as good thermal productivity has made it a fuel of choice in case of homogeneous charge compression ignition (HCCI) and reactivity controlled compression ignition(RCCI) engines (Gwalwanshi et al., 2022). Both biobutanol and bioethanol have the ability to upgrade engine efficiency, ignition capacity and reduce harmful gaseous releases into the environment (Yusoff, et al., 2015).

Bio-succinic acid the amongst methods used for the bio-succinic acid production, simultaneous saccharification and fermentation (SSF) is designated as the most popular method because it allows both the major processes (sugar hydrolysis and fermentation) to take place at the same time thus saving time. The entire process of producing this biochemical from apple pomace can be divided into three steps. First step consists of collection and storage of apple pomace. Storage is followed by tray drying to increase shelf-life. At last, it is transferred into silos to avoid any contamination. Second step comprises of inoculums preparation using *Actinobacillus succinogenes* cells followed by simultaneous saccharification and fermentation (SSF). Third step involves biosuccinic acid purification using ultra filtration (Gonzalez – Garciaet al., 2018).

Bio-succinic acid can function as an important intermediary forthe production of variety of chemicals which hold importance in the manufacturing sector (Saxena et al., 2017). For instance, it can be used to prepare chemicals like adipic acid, tetrahydrofuran, succinimide, resins etc, which find large scale applications in nutriment and synthetic manufacturing sectors (Sharma et al., 2020). It also has the capability to function as growth controller in plants like wild carrots thus supporting the proper growth and helping them to collect polyphenols (Dougall and Weyrauch, 1980). It is reported to be very effective in treating prolonged sickness or wound by acting as a tranquilising agent or as a spasm suppressant (Macagnan et al., 2015).

Furthermore, it helps in restoring the normal functioning of the body whenever an athlete is under physical stress/strain while undergoing physical training (Voitenko et al., 2019). Headaches caused after alcohol consumption can be cured by taking biosuccinic acid as it increases the capacity of the human digestive tract to act upon acetaldehyde which is the main metabolite of alcohol (Saxena et al., 2017).

Ecofriendly solvents like dimethyl succinate can be obtained by interesterification of biosuccinic acid (Glassner et al., 1995). Mixtures made from biosuccinic acid can be employed as taste amplifiers in food and might act as a salt replacer as well(Turk, 1993). Biosuccinate salts can be added into the fodder for ruminants in order to escalate propionate (predecessor for glucose formulation) generation in rumen (Bergen and Bates, 1984) thus helping them to fulfill their glucose needs (Reis et al., 2014). Also, pure raw form of biosuccinate salt can open new avenues into the existing animal fodder retail sector by functioning as are placement for germicidals (monocin and lasalocid) (Bergen and Bates, 1984). This salt can enhance fodder's nutrition profile and thus eliminate the need of adding antibiotics into them (Yao et al., 2017).

Wet strength and water repulsion capacity of leather is ameliorated in tanneries using biosuccinic acid (Ozcan et al., 2003). It also enhances the froth formation when metal ores arebeing concentrated and their surfaces are being transformed into hydrophobic or hydrophilic (Ozcan et al., 2003). In the paint industry, it is used for making blends because it acts as a good coalescing medium for emulsion formation (Lee et al., 1999). Bionelle, an environmentally–safe polymer produced using bio-succinic acid and 1,4 – butanediol, is the most recent utilization of the acid (Vashisht et al., 2019).

Acetic acid production can also be achieved through apple pomace valorization (Vashisht et al., 2019). Since most of the methods reported in literature involve synthetic processing, using apple pomace to produce acetic acid will be a significant step towards achieving environmental sustainability (Parmar and Rupasinghe, 2013). Apple pomace, which constitutes 30% of the intact fruit, has a lot of untapped potential when it comes to acetic acid production. This potential must be unleashed by employing the correct microorganism for apple pomace fermentation. On similar lines, earlier studies reported acetic acid production using *Acetobacterpasteurianus*, in which apple pomace is first fermented to produce bioethanol followed by acid production (Vashisht et al., 2019). Thus, an environment friendly process was devised for acetic acid production which was entirely based on microbial principles without involving the use of single commercial enzyme.

Acetic acid has been used since centuries to treat injuries by functioning as a local antiseptic due to its excellent prophylactic properties (Ryssel et al., 2009). It possesses medicinal properties which can help to treat prolonged and digestive concomitant disorders (Daniela et al., 2021). It is found to be very helpful in treating type 2 diabetes (Ho et al., 2021) by managing glucose levels and increasing insulin release (Shishehbor et al., 2017). It is also used in orthopedic surgery to remove damaged tissues from the wound, protein or polysaccharide layers formed on the skin during the operation, patches formed during severe injuries (Hashmi et al., 2022). Hepato cellular carcinoma(HCC),the fifth most prevalent cancer worldwide, can be cured by administering acetic acid into the skin through injections or at least, its timely injection into the body can help to resort to less intruding healing mechanisms other than surgery (Weis et al., 2015).It is also used to conduct cervical cancer screening tests in areas which are less advanced in terms of technology and infrastructure (Wu et al., 2003; Mandel blatt et al., 2020).Apart from the direct applications in the medical industry, acetic acid is used extensively in chicken broilers (Dourado et al., 2022) and meatproducts such as beef cuts or minced beef(Harris et al., 2012) to reduce the percentage of harmful microorganisms such as *Escherichia coli* and *Salmonella*. Lastly, it is also used in the aquatic biofouling industry as an effective anti-fouling agent and is observed to be working against a variety of fouling organisms (Forrest et al., 2007).

Pectin, a biomolecule, can also be extracted using apple pomace. Usually, pectin extraction from food waste is achieved through acid, alkali or enzymatic method but something which is more sustainable than all of these is the use of eutectic solvents (Chen and Lahaye, 2021). Eutectic solvents are economical and environment friendly as they comprise of simple sugars, amino acids or organic acids which are all biodegradable in nature. Pectin extraction using apple pomace with the help of these solvents is even better than extraction techniques like microwave assisted extraction (MAE), subcritical water extraction (SWE) or ultrasound. This is because MAE, SWE or ultrasound take a lot of equipment and investment cost if one wants to take the technologies to an industrial level but this is not the case when it comes to these solvents. They take minimum input in comparison to all these technologies. Furthermore, these solvents have unique capability of being customized as per the extraction needs which makes them more attractive as an extraction method. Therefore, choline chloride and lactic acid eutectic solvent mixture helped in pectin extraction as a pre treatment agent whereas choline chloride and urea solvent mixture worked in functionalizing pectin before the main extraction. In both the cases, pectin extraction was achieved using apple pomace but the eutectic solvents performed different functions to ease the extraction process. One worked for pretreatment while the other worked in functionalizing pectin (Chen and Lahaye, 2021).

Functional foods

Functional foods are the foods which aim to provide health-benefitting attributes to the consumer in addition to basic nutrition (Kaur and Das, 2011). These foods aid in preventing life style related disorders through regulation of central and peripheral system, improvement of body's defense mechanism by activating immune system and repressing allergies (Mitsuoka, 2014). They promote overall well-being by protecting against high blood pressure, diabetes mellitus, cancer, high blood cholesterol, anemia and platelet accumulation(Arai, 1996). They look very much similar to any traditional food andcan be consumed as part of the everyday diet (Saher et al., 2004).

Apple pomace is widely used in the food industry for preparation of functional foods (Lyu et al., 2020). A research group prepared gluten free brown rice crackers for celiac patients by incorporating apple pomace in rice blends (Mir et al., 2017). Basically four pomace flour blends (pomace + rice flour) were prepared wherein 0%, 3%, 6% and 9% apple pomace was incorporate into the flour. Results showed that as the apple pomace amount increased in the flour, its antioxidant nature, dietary fiber content and mineral content also increased by 4%, 3% and 7% respectively thus making it an apt functional food. Similar was the case when apple pomace was incorporated in extruded snacks or baked scones (Reis et al., 2014). As the percentage of phenolic compounds, fiber and antioxidants rises, the product becomes enriched to treat a number of diseases (Skinner et al., 2019). Functional yoghurt can also be prepared using apple pomace as a sustainable food constituent (Reis et al., 2014). Apple pomace have been added into bread which greatly improved its flavor and permeability (Pyanikova et al., 2021). The plas prepared using 9% apple pomace showed lower glycemic index(63.38GI) than the control the plas which had 68.1GI (Waghmare et al., 2014). Apple pomace have been integrated into corn based formulations to manufacture snacks with low expansion ratio and factorability (Ackar et al., 2018).Apple pomace has been used as an encapsulating agent in case of lactic acid bacteria (a probiotic) to enhance its survival rate in the human gastrointestinal tract(Serrano-Casas et al., 2017). Incorporation of apple pomace (10%) into noodles improved its quality in terms of protein content (10.20% to 11.80%), dietary fiber content (6.0% to 13.28%) and antioxidant activity (Yadav and Gupta, 2015).

Cosmetic products

As the consumers are getting more and more interested in natural products (Chisti, 2008), it has become the utmost responsibility of the cosmetic industry to indulge into sustainable beauty products. The industry is now rigorously looking for sustainable alternatives to treat skin problems like wrinkles, excessive pigmentation etc. so that they can stay relevant in the market. Polyphenols from apple pomace can serve as a very good solution in this context (Dias et al., 2021).

For instance, quercetin (a phenolic compound), extracted from apple pomace has the potential to function treat skin problems because of its antipyretic properties (Lee et al., 2013). It reduces reactive oxygen species (ROS) formation thus exhibiting its antioxidant property which ultimately results into better skin (Lee et al., 2013). Moreover, apple pomace polyphenols can remarkably repair in problems like dark spots, collagen damage caused due to sun rays (especially UV-Arays) through numerous routes. Figure 1 depicts potential ability of apple pomace polyphenols. Another apple pomace compound which can contribute immensely to dermal formulations is pectin due to its good gelling properties (Arraibi et al., 2021).

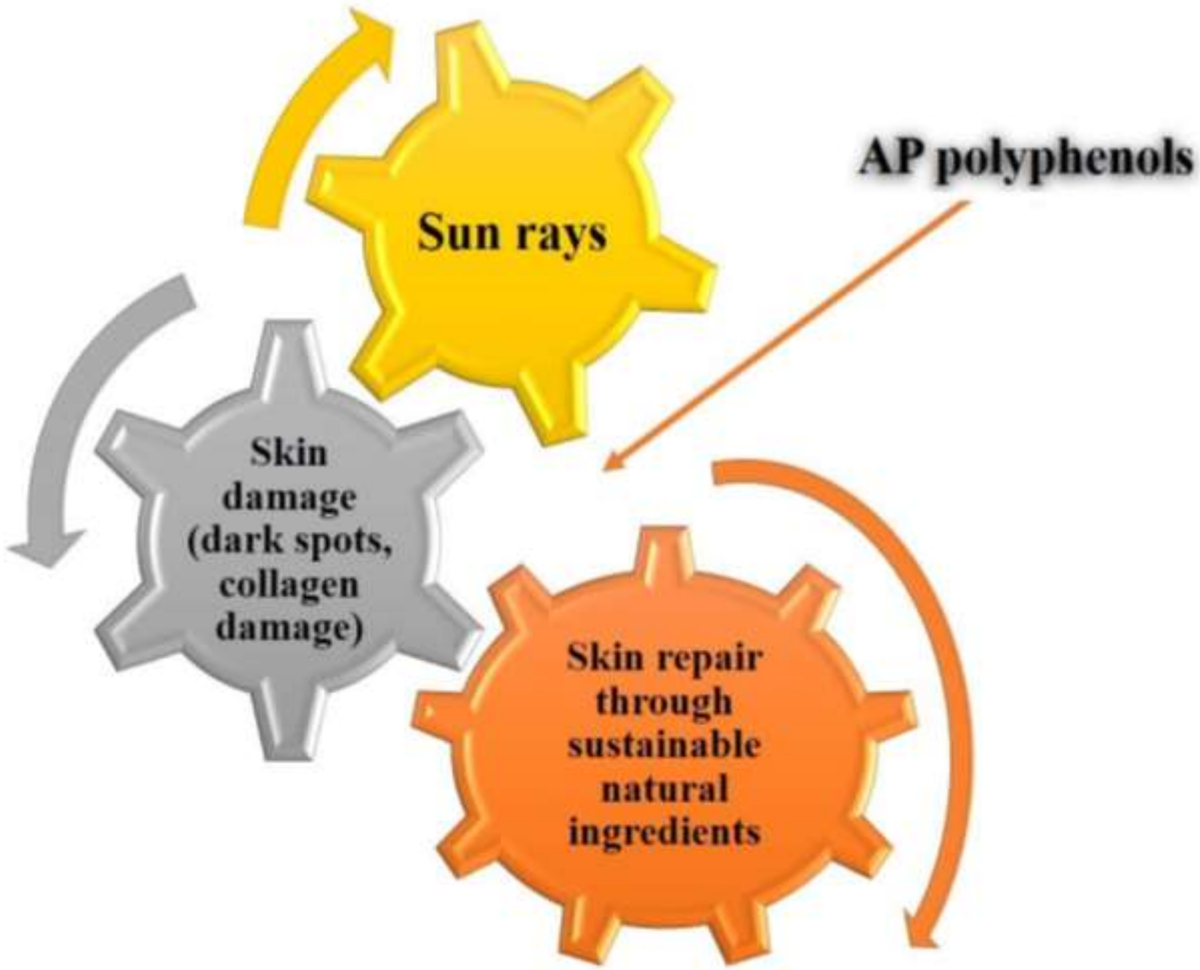

Fig 1: Role of AP polyphenols

Bioplastics

According to International Union of Pure and Applied Chemistry (IUPAC), bioplastics are defined as a biobased polymer or a polymer issued from them on polymers derived from the biomass (Nandakumar et al., 2021; Vert et al., 2012). These polymers can be either naturally derived or compostable or at times, they can have both the attributes (Döhler et al., 2022). Apple pomace can serve as a promising source for production of a bioplastic named poly-hydroxyalkanoates(PHA)(Liu et al., 2021). PHA is a class of naturally existing polyesters synthesized using around 700 to 30,000 (R)-hydroxy fatty acid monomer entities (Liu et al., 2021). They are generally produced using chemical digestion or solvent extraction which involve high economic cost and cause enormous environmental pollution (Leong et al., 2017). In such a scenario, apple pomace can act as a good carbon substrate for PHA production. Moreover, its fiber and polyphenol-rich ability aids in the PHA formation. It has been prepared using mixed culture of *Cupriavidusnecator* and *Pseudomonascitronellolis* in which apple pomace has been employed as the sole carbon source (Rebocho et al., 2019).

A biorefinery is a sustainable series to transform an organic matter (apple pomace, in this case) into an array of valuable products and energy (Galanopoulos et al., 2020). The aim of operating any bio refinery is zero waste generation thus achieving true sustainability. Another important goal is to achieve optimization throughout the process, whether it is the apple pomace constituent's metamorphosis process or the range of products obtained after valorization (Awasthi et al., 2021). Thus, zero-waste generation and process optimization are the two main attributes of a sustainable biorefinery.

Modern biorefineries must target towards becoming centripetal so that novel techniques can be integrated within industrial requirements. As a result, heterogeneity (Ferreira and Taherzadeh, 2020) will be achieved which will pave way for quality products. Figure 2 depicts a schematic diagram to nurture a biorefinery which can yield heterogeneity. One such example which serves as a good combination of an integrated approach and diversification is that of apple pomace valorization using anaerobic digestion along with novel extraction techniques. This procedure can be used to produce value-added compounds like pectin, lignin, dietary fibers, laccase (Xin and Geng, 2011). A study conducted by Chandra et al. On dairy waste water biorefinery highlights the importance of Biorefinery Complexity Index (BCI) to achieve biorefinery sustainability/ feasibility (Chandra et al., 2018). A similar study can be conducted to analyse apple pomace biorefinery in order to know how sustainable it can be in the long run. As biorefineries are optimized to achieve more and more products with the use of latest technologies, their working tends to get complicated (Maria and Gerfried, 2019). Amidst all this, one needs to keep track of the fact that how sustainable a biorefinery is. BCI helps to achieve this goal. The more the BCI value, the less is the process feasibility / sustainability. Dairy waste water treatment study provided a BCI of 20, which means a sustainable biorefinery (Chandra et al., 2018). This value can be used as a landmark foran apple pomace biorefinery sustainability feature. There are several other examples available, this being the latest one. Before conducting a BCI study, there are some presumptions (Maria and Gerfried, 2019) to be made. These are as follows:

- As the biorefinery characteristics increase, it tends to get much more complicated.

- As a technique/an application becomes at par with the commercially available technology, its Technique Readiness Level (TRL) increases. The more the TRL, the less is the financial and ecological risk involved in a process. Therefore, lower is the process complexity.
- TRL is akin to "Market Readiness Level (MRL)". So, only TRL values are used.
- BCI is dependent upon the number of biorefinery characteristics and the irrespective TRLs
- In case of a modern biorefinery, all features are commercially updated. So, complexity is measured simply by the number of features. On the other hand, one needs to consider the TRL as well in case of conventional processes where technologies are still not commercially relevant.

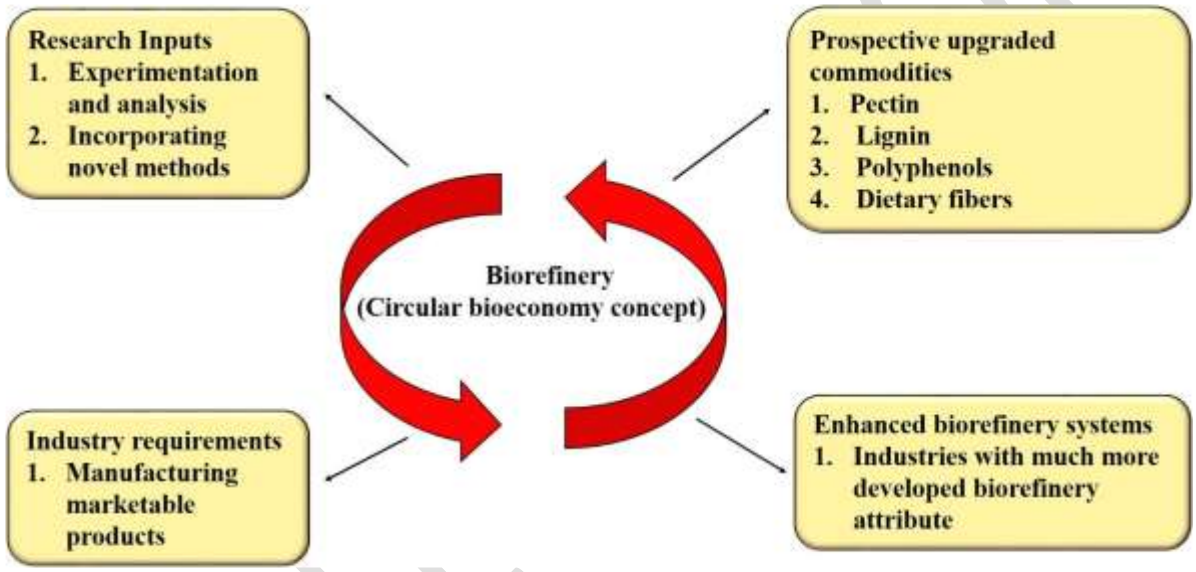

Fig 2: Nurturing a bio-refinery to provide potential outputs

There are four characteristics to be considered in a biorefinery: Platforms, Feedstock's, Products and Processes. These four characteristics will have their respective TRL ranging anywhere between 1 to 9. 1 represents "basic level" whereas 9 represents "highest accomplishment of a technology". As it can be inferred, the number 1 marks the fact that the technology is still not marketable whereas the value 9 characteristic is the most marketable technology. Once the TRL of every character is determined, character complexity (CC) of each of the four features is calculated. The formula for calculating CC is (10-TRL). Next step is to calculate the "character complexity index (CCI)"of each character. The total of these 4CCIs provides the final BCI value for any biorefinery. Therefore, BCI = CCI (platforms) + CCI (feedstocks) + CCI (products) + CCI (processes). Let us learn to calculate BCI with the help of a simple example of an oil biorefinery (Maria and Gerfried, 2019). The oil biorefinery being considered here comprises of one platform i.e. oil, one feedstock (starting material) i.e. oil seed crops, three products i.e. biodiesel, glycerin and feed, three processes i.e. pressing, esterification and distillation. So, the following are the values of the four CCIs:CCI (platform)=1,CCI(feedstocks)=1,CCI(products)=3,CCI(processes)=3. Therefore, BCI=1+1+3+3=8. BCI can be similarly calculated for apple pomace biorefinery for its sustainability evaluation. Sustainable development remains in complete without conducting an LCA study (Chang et al., 2014). As the name suggests, it assesses the life cycle of the commodity (apple pomace, in this case) (Rebitzer et al., 2004). It provides a detailed account of all the environmental emissions associated with a product (Hellweg and Milà I Canals, 2014). Studies must focus on analyzing the different stages of an agricultural waste product because research in this area is very much restricted (Yaashikaa et al., 2022). Moreover, a grarian sector is much more difficult to evaluate as compared to a manufacturing unit. For instance, numerous issues like intense surveys and statistics, unpredictability of end results etc. would crop up in LCA of apple pomace valorization. Every step of an LCA study is targeted towards achieving a "circular bioeconomy "thus reducing environmental damage (Fang et al., 2021). Figure 3 highlights the procedure for implementing LCA to apple pomace valorization.

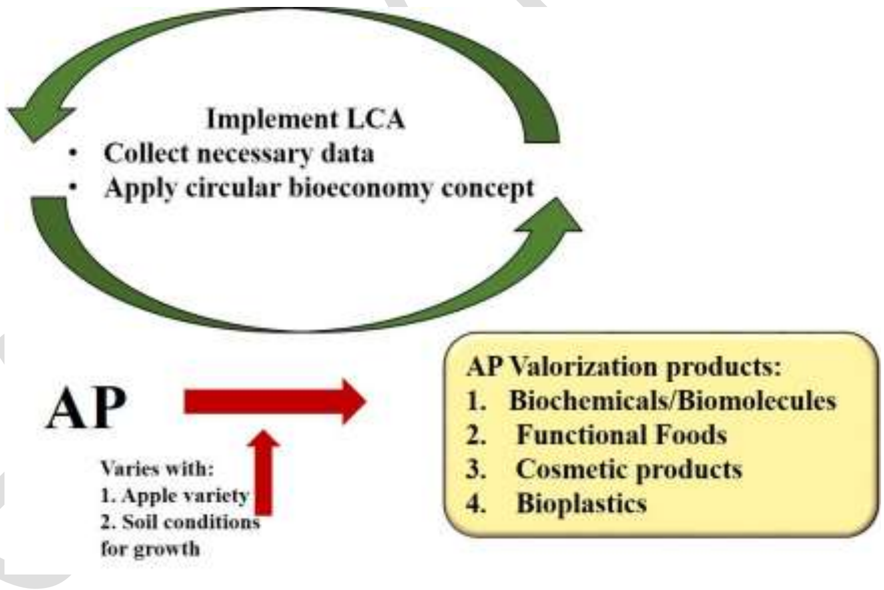

Fig 3. Implementing LCA to AP optimization

Conclusion

Apples, being one of the most produced fruits in the world, paveway for an extensive amount of apple pomace generation through processing of products such as apple cider, jam, juice etc. Studies report that apple pomace has huge potential in terms of its rich composition of proteins, minerals, dietary fibers, antioxidants. In order to harness this treasure house of nutrients, various biochemicals can be produced using apple pomace. For instance, biochemicals like lactic acid, biobutanol, bioethanol, bio-succinic acid, pectin can be produced from apple pomace fermentation by employing different microorganisms. These biochemicals find very useful applications in the pharmaceutical industry, food industry, marine biofouling sector, leather industry etc. Affluent profile of apple pomace can also be exploited for production of functional foods which are low in glycemic index (GI) and offer benefits like low expansion ratio and factorability. Highly nutritive noodles rich in protein and dietary fiber amount along with good antioxidant content can also be manufactured using apple pomace. Furthermore, quercetin-based cosmetic products can be made using apple pomace which can help us to treat several skin problems like wrinkles and pigmentation in a natural way. Lastly, biobased polymers such as poly hydroxyl alkanoates (PHA) can be manufactured using apple pomace as the main carbon source in the polymer production process. These goals can be achieved in the most sustainable manner through construction of apple pomace biorefineries where life cycle assessment (LCA) studies are conducted from time to time.

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Conflict of interest statement

The authors declare that there is no conflict of interest in publication of this article.

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