6. SUSTAINABLE MANAGEMENT OF FRUIT WASTE PRODUCTION

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Abstract

The main goal of this paper is to review sustainable strategies presented in the literature for managing fruit processing by-products according to the circular economy, which could be useful for companies. In the food processing of fruits, the waste can be utilised directly or indirectly. The direct utilisation of fruit waste does not ensure full valorisation and does not fully minimise the environmental impact. The most sustainable management for the full valorisation of fruit waste according to the circular economy is the indirect utilisation, which requires an energy-intensive drying process before the biorefinery approach. Sustainable Development Goal (SDG) 12.3 promotes the reduction of food waste and food loss throughout the supply chain to achieve sustainable development by 2030, especially at retail and consumption levels. The fruit processing industry produces large amounts of by-products, mainly removed by landfilling or incineration. However, these methods cause emissions of carbon dioxide, methane and ammonia, and release dioxin into the environment. In addition, it causes a loss of valuable biomass and nutrients and an economic loss. The sustainable management of fruit processing by-products is important to reduce the amount of food waste deposited in landfills and to develop strategies through their reuse for full valorisation and added economic value. The currently proposed biorefinery only focuses on partial valorisation of fruit waste, which is not completely compatible with the closed-loop economy framework and economically feasible due to the low-efficiency bioprocesses. Therefore, there is a need for sustainable conception in the biorefinery approach, which can provide full valorisation of fruit waste according to the circular economy.

Keywords: fruit by-products, sustainable strategies, management of by-products, circular economy.

JEL codes: Q01, Q16, Q42, Q53, Q55, Q56.

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Introduction

The global production of fruit waste only generated by the processing industry is estimated at more than 190 million tons per year (FAOSTAT database). Currently, fruit waste management has an impact on the environment and is not in agreement with the circular economy because it is landfilled in composting plants or fed into the fermentation process of biogas plants. However, these methods cause greenhouse emissions and release waste into the environment. In addition, it causes a loss of valuable biomass, nutrients and an economic loss.

In the literature, there are many sustainable strategies for the valorisation of fruit waste mainly under a biorefinery approach to produce bio-products, biofuels, biofertilizers and bioenergy (Pathak et al., 2016; F. Zhang et al., 2021). The purpose of a biorefinery system is to minimise the impact on the environment by reducing fruit waste volumes accumulated in landfills and the use of closed-loop economy processes. However, currently, the proposed biorefinery only focuses on partial valorisation of fruit waste, which is not completely compatible with the closed-loop economy framework and is not economically feasible due to the low-efficiency bioprocesses. Therefore, there is a need for sustainable conception in the biorefinery approach, which can provide a full valorisation of fruit waste according to the circular economy. Only biorefinery in the closed-loop technology is a promising way to enhance economic efficiency and decrease the environmental influence according to sustainable development.

In this context, this review analyses the sustainable management of fruit processing by-products in a biorefinery approach to achieve their full valorisation according to the circular economy. Additional complete valorisation is discussed in five main stages, namely: pretreatment, extraction, dark or aerobic fermentation, anaerobic digestion and posttreatment.

6.1. Economic determinants of fruit waste production in Poland

The food sector is one of the most important and fastest-growing branches of the Polish economy. Poland is one of the largest fruit producers in Europe. In 2021, it was third behind Spain and Italy. In 2022, more than 5.28 million tons of fruit were produced in Poland, with apples, berries and cherries having the largest share (Table 6.1). Apples constituted by far the largest proportion of all fruit produced in Poland in the last 5 years (79.13%). Berries harvest in Poland accounted for 11.49% of all fruit production in Poland during the analysed period (Nosecka, 2022).

Table 6.1. Fruit production in Poland in 2018–2022

Specification	Harvest (in thousand tons)					Harvest structure (average value 2018–2022) (%)
	2018	2019	2020	2021	2022	
Fruits—total	5072.5	3938.0	4518.4	5059.5	5282.5	
Apples	3999.5	3080.6	3555.2	4067.4	4200.0	79.13
Strawberries	195.6	177.0	146.0	155.9	180.0	3.61
Sour cherries	200.6	151.9	155.5	166.6	183.0	3.60
Currants	164.6	126.2	145.9	152.0	142.0	3.07
Plums	121.1	95.0	111.7	117.4	132.0	2.42
Raspberries	115.6	75.7	123.2	103.9	105.0	2.19
Pears	90.9	67.6	61.0	68.6	80.0	1.55
Cherries	60.0	44.4	51.3	59.1	77.0	1.21
Chokeberries	50.2	40.8	66.1	66.0	55.0	1.17
Highbush blueberries	25.3	34.8	55.3	55.3	64.0	0.98
Other berries	8.3	6.8	16.0	15.5	23.0	0.29
Gooseberries	11.5	9.6	9.6	9.8	10.0	0.21
Walnuts	8.5	5.2	7.0	6.8	11.0	0.16
Hazelnuts	6.6	5.4	7.7	7.6	9.5	0.15
Peaches	10.6	8.5	3.8	4.5	6.5	0.14
Apricots	3.6	3.1	3.1	3.1	4.5	0.07

Source: (Nosecka, 2022).

The fruit industry processes fruit mostly into concentrated juices, frozen fruit, fruit concentrates and jams. The preserve production forecast was to reach 1.17 million tons in 2022/2023, up from 1.13 in the previous year. The total production of concentrated juices, nectars and beverages was to reach 2.23 million tons (compared to 2.27 million tons in the previous year). In the 2021/2022 season, 83.9% of apples, 32.9% of strawberries, 28.7% of raspberries and 47.6% of currants were allocated to the processing of concentrated juices. A similar structure of fruit allocation was forecast for the 2022/2023 season (Nosecka, 2022).

Generally, fruit waste can be generated at two stages: fruit processing and food processing (Figure 6.1).

During the fruit preparation process, waste takes the form of leaves, fruit stems and spoiled, damaged fruit, which is about 0.5% of the fruit weight (Lipiński et al., 2018). However, in the case of food processing, waste is generated mainly in the form of pomace, peels, cores, seeds and tails, which amounts to 20%–60% of the fruit weight, depending on the fruit and technological process (Bayram et al., 2021; Lau et al., 2021).

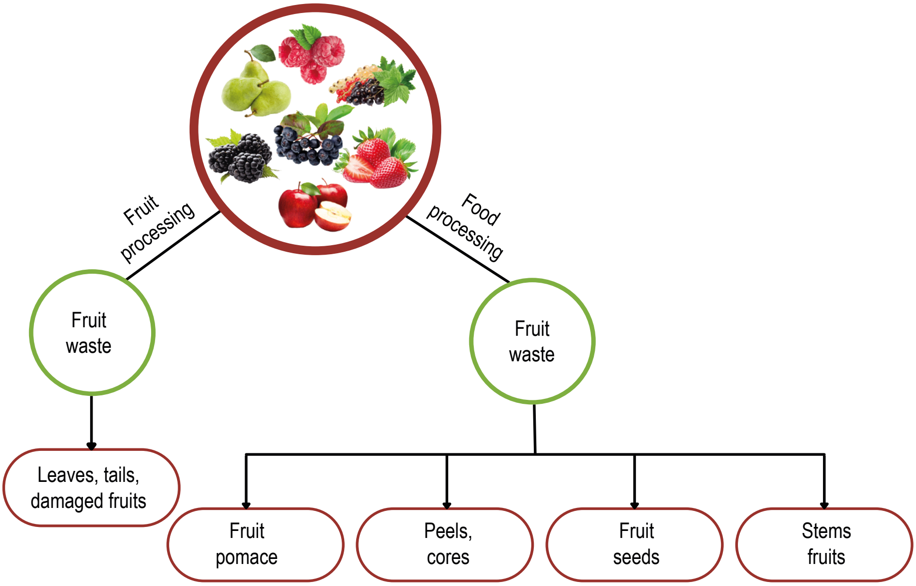

Figure 6.1. Stages of fruit waste production
Source: own compilation.

6.2. Fruit waste composition

Fruit waste is well known for its high content of bioactive compounds with antioxidant and antimicrobial properties such as flavonoids, tannins and phenolic acids. Especially, fruit pomace contains a high content of bioactive substances, reaching up to 80% of their total content in fruit (Cubero-Cardoso et al., 2020; Ovcharova et al., 2016; Reguengo et al., 2022; Reynoso-Camacho et al., 2021; Tian et al., 2018). Figure 6.2 shows the general structure of the phytochemicals contained in fruit by-products.

Due to its high polysaccharide content, the presence of mono-, di- and oligosaccharides, as well as citric and malic acid, apple pomace is considered to be a potential source for the extraction of value-added compounds such as simple sugars like glucose, fructose, and sucrose. It is also a rich source of carbohydrates, pectin, crude fibre, proteins, vitamins and minerals and, as such, is a good source of nutrients worth recovering (O'Shea et al., 2015). Furthermore, residues from the production of blueberry juice are also a valuable source of health-promoting compounds. Berry pomace has a high concentration of anthocyanins and polyphenols. It also comprises modest quantities of hydroxycinnamic acids (Kylli, 2011; Maatta-Riihinen et al., 2004). However, the highest contents for p-coumaric acid, chlorogenic acid and caffeic acid are found in blueberries, chokeberries, highbush

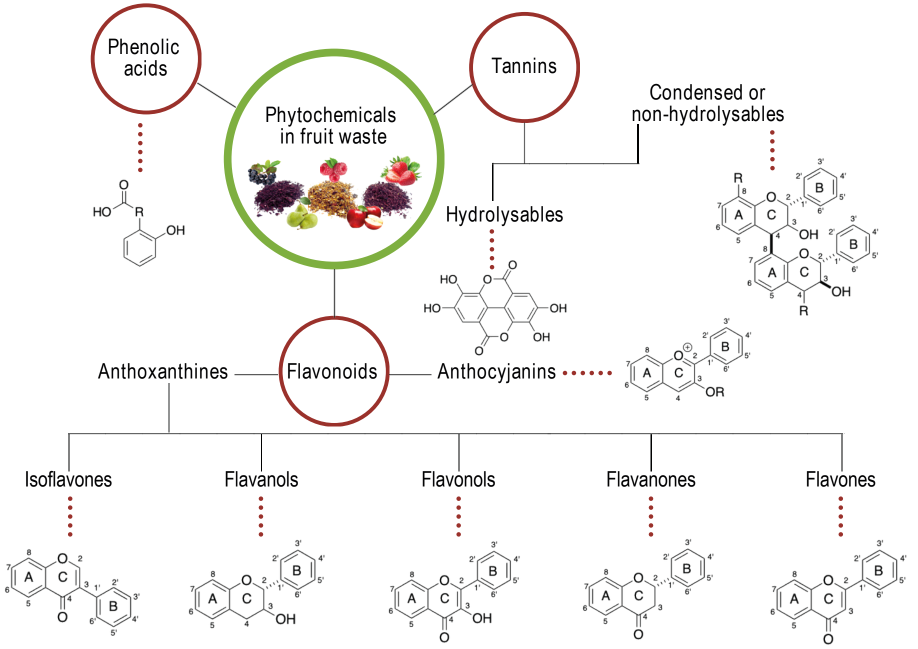

Figure 6.2. General structure of phytochemicals contained in fruit by-products
Source: own compilation.

blueberries, American cranberries, blackcurrants and lingonberries, which have the highest levels of flavonoids, particularly aglycones and derivatives of quercetin and myricetin (Häkkinen et al., 1999; Koponen et al., 2007; Kylli, 2011; Maatta-Riihinen et al., 2004).

6.3. Directions in fruit waste production

Recently, what seems to be an emerging issue is finding an integrated technology for fruit waste recycling, resource recovery and the production of high-value products under the circular economy scheme with a minimal environmental impact (Borujeni, Karimi et al., 2022; Costa et al., 2022; Górnaś et al., 2016; Mirabella et al., 2014). In the case of food processing of fruit, the waste can be utilised directly or indirectly (Figure 6.3).

In the direct utilisation of fruit, waste can be landfilled in composting plants or can be subjected to aerobic or anaerobic fermentation (Figure 6.4). This way of fruit waste management can be used when the microbial quality of the fruit waste is low. During the aerobic fermentation compost is formed which is used as organic fertiliser. However, better valorisation can be achieved by the anaerobic digestion, which leads to the production of biogas and post-fermentation waste, which in

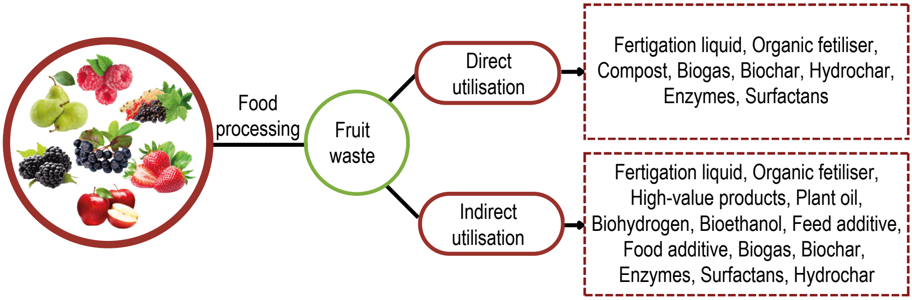

Figure 6.3. Strategies to use fruit waste after food processing
Source: own compilation.

turn can be transferred to biochar or harmless organic fertiliser and fertigation liquid. However, the direct utilisation of fruit waste results in the loss of bioactive substances contained in them. What is more, greenhouse gases are emitted during composting. It means that this management method does not ensure full valorisation of fruit waste and does not fully minimise the environmental impact.

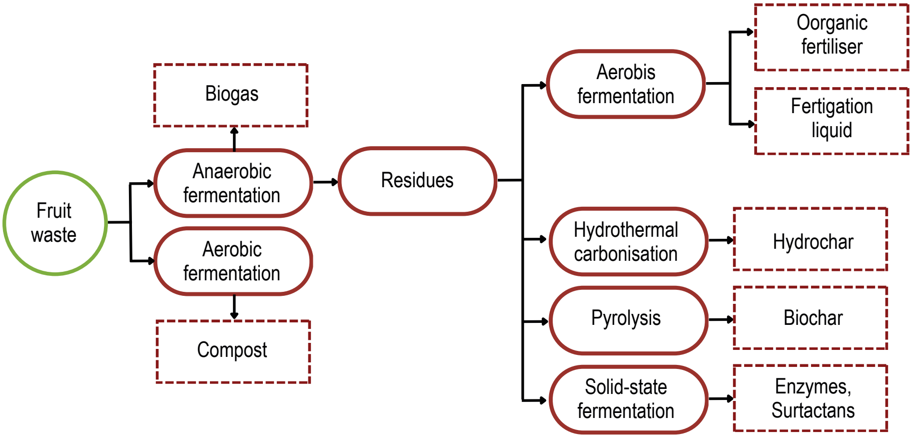

Figure 6.4. Direct utilisation of fruit waste after food processing
Source: own compilation.

On the other hand, the indirect utilisation is the most sustainable strategy for the full valorisation of fruit waste according to the circular economy. At the beginning, the fruit waste is subjected to a drying process and then to further stages of biorefining, such as:

- the process of extraction,
- dark fermentation,
- aerobic fermentation,
- anaerobic fermentation (Figure 6.5).

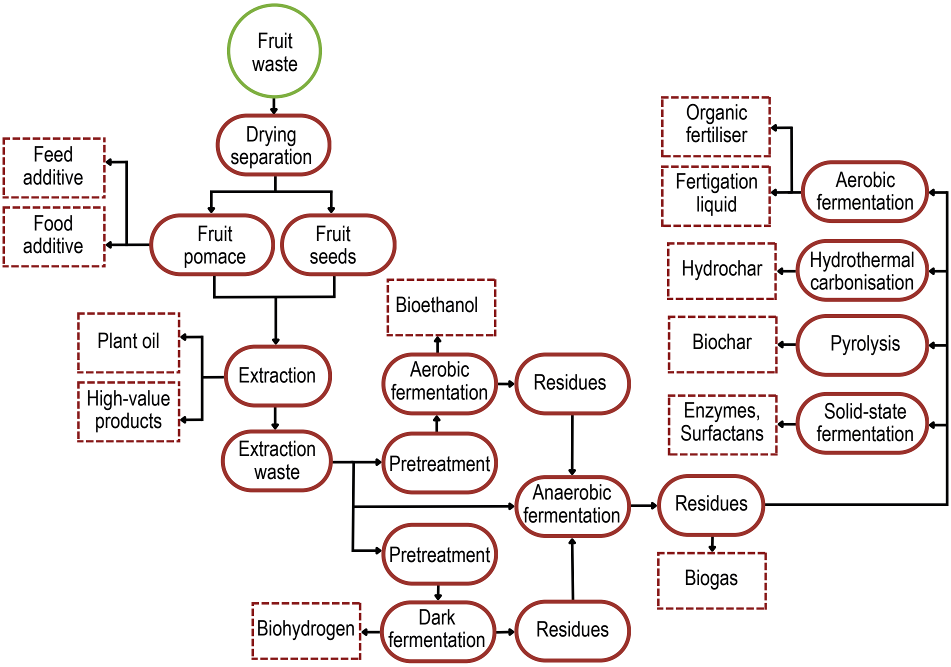

Figure 6.5. Indirect utilisation of fruit waste after food processing
Source: own compilation.

6.3.1. Drying process

After the production of juices and smoothies, fruit waste contains large amounts of water (about 70%) that must be removed to ensure its microbiological stability (to about 5%). Currently, several drying methods are being investigated for fruit pomace (Radojčin et al., 2021). From a practical point of view, the most often applied drying techniques are forced air and freeze-drying methods. The biggest concern with drying is that the bioactive compounds in fruit by-products are sensitive to heat and oxygen. Several studies have evaluated the effects of different drying methods on the degradation of bioactive compounds from fruit pomace (Vashisth et al., 2011). The freeze-drying method guarantees the best quality of the obtained dried pomace. However, it is not very widely used due to the long water removal time, which is associated with high-energy consumption. Therefore, other methods such as sun or hot air drying are applied in the industry. For full valorisation of fruit pomace, it is critical to define drying conditions that can maximise the retention of bioactive compounds while remaining economically feasible on a larger industrial scale.

6.3.2. Extraction process

Depending on the quality parameters, dried fruit pomace can either be used directly as food and feed additives (Nawirska, 2005) or can be ground, and then fruit seeds can be separated from the fruit pomace powder. The fruit seeds can be used for oil extraction with mechanical or chemical methods. The fruit pomace without seeds can be subjected to an extraction process to recover bioactive compounds, e.g., pectin, anthocyanins, polyphenols, and proanthocyanidins. The recovered natural bioactive substances can be used in the food, pharmaceutical or cosmetic industries. These substances can be extracted using conventional or non-conventional techniques. The conventional extraction techniques include maceration and Soxhlet extraction, which requires a large volume of solvent and heat, making these methods time and energy-consuming (Rodriguez & Raghavan, 2021; Q. Zhang et al., 2018). Apart from that, they are less suitable for heat-sensitive ingredients. To overcome the disadvantages of these techniques, there are other extraction methods, such as unconventional or green extraction, that exhibit shorter extraction times, high yield and selectivity as well as lower solvent consumption (Azmir et al., 2013; Chemat et al., 2012). Among the examples of these techniques are ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, enzyme-assisted extraction and pulsed electric field extraction (Sagar et al., 2018). They can improve the extraction of heat-sensitive bioactive ingredients due to lower processing temperatures. To fully utilise fruit by-products, it is critical to optimise extraction methods and conditions that can maximise the recovery of bioactive compounds while remaining economically feasible on a larger industrial scale (Tao et al., 2014).

The extraction residue can be directly transferred to anaerobic digestion or it can go through the pretreatment process before dark or aerobic fermentation. Pretreatment with enzymes, bases, inorganic acids or physical techniques is required to hydrolyse non-fermentable sugars.

6.3.3. Dark fermentation (DF)

Among all biohydrogen production technologies, DF is the most promising one due to the low energy input and lack of oxygen generation (Basak et al., 2020; Hay et al., 2013). In this process, fruit waste is converted to a mixed gas containing H_2, CO_2, H_2S, CO and CH_4, organic acids and alcohols using anaerobic bacteria (*Clostridium*, *Enterobacter* and *Bacillus*) in the absence of light and oxygen (Table 6.2).

Until now, the maximum yield of hydrogen production through the DF process is 4 moles of H_2 per hexose molecule, which is equal to 33% (on sugars). Apart

Table 6.2. Apple waste as substrate for bio-H_2 production in DF

Substrate	Microorganisms	Pretreatment	Bio-H_2 production [mL/g TS*]	Reference
Apple peel	microbial consortium	not applied H_2SO_4 solution NH_3 liquor	41.28 76.68 101.08	Feng et al., 2010
Apple pomace	rice rhizosphere microflora	not applied	90	Doi et al., 2010

* TS – total solids.

Source: own elaboration.

from that, hydrogen production through DF leads to a negative net energy balance (Martinez-Merino et al., 2013). Therefore, in order to increase the hydrogen yield production, residue in the form of organic acids/alcohols is utilised in anaerobic digestion to provide biomethane (Redwood et al., 2009).

Many studies have focused especially on the production of bio-H_2 from food waste, while there are only a few studies investigating the production of bio-H_2 from fruit by-products. Feng et al. (2010) have examined acid and base pretreatment of apple peels to produce bio-H_2 with river sludge. On the other hand, Hwang et al. (2011) have not applied any pretreatment processes. In fact, they studied a two-stage fermentation system (dark/dark) with sewage sludge fed with different ripened fruit feedstocks. In the two-stage system, the energy efficiency (H_2 conversion) obtained from mixed fruit waste increased from 4.6% (in the first stage) to 15.5% (in the second stage), which indicated the energy efficiency can be improved by the combined H_2 production process.

6.3.4. Aerobic fermentation (AF)

Fruit pomace, or the extraction residue, consists of fermentable sugars and insoluble polysaccharides and therefore can be converted into bioethanol or biobutanol by alcoholic or acetone-butanol-ethanol fermentation. Production of these biocompounds required the following three steps: pretreatment, hydrolysis and sugar fermentation processes. The aim of the pretreatment is to prevent lignin against substrate degradation and inhibitors, which leads to an increase in ethanol production efficiency. The most commonly used pretreatment methods are mechanical and physicochemical processes such as milling, steam explosion, griding and acidic, alkalic or organosolv heating (Table 6.3).

In the second step of bioethanol production, enzyme hydrolysis or acid hydrolysis is applied to form fermentable sugars from fruit pomace, which consists of cellulose, hemicellulose, pectin and lignin. To overcome the problem with pectin and lignin, high enzyme loadings, such as pectinase, cellulase and glucosidase, are required, where the high cost of applied enzymes influences the economic

Table 6.3. Apple pomace as a substrate for bioethanol production

Substrate	Pretreatment	Enzymes	Microorganism	Ethanol production	Reference
Apple pomace	acidic heating	cellulase	*S. cerevisiae*	1.10 g/L-h	Demiray et al., 2021
Apple pomace	alkalic heating	pectinase cellulase hemicellulase	*S. cerevisiae*	1.5 g/L-h	Magyar et al., 2016
Apple pomace	acidic treatment	pectinase cellulase hemicellulase	*S. cerevisiae*	190 g/kg	Parmar & Rupasinghe, 2013
Apple pomace	ethanol treatment	pectinase cellulase hemicellulase	*S. cerevisiae*	173.3 g/kg	Borujeni, Alavijeh et al., 2023

Source: own elaboration.

viability of ethanol production. Therefore, to decrease the cost of production, in-house enzymes were applied (Choi et al., 2015).

The last stage of bioethanol production is the fermentation process carried out mainly with industrial microorganisms such as *Saccharomyces cerevisiae.* Due to the high free sugar content in fruit pomace and less fermentation inhibitor formation, the productivity of bioethanol is much higher (1.1–4.7 g/L-h) than with lignocellulosic biomass (0.1–0.9 g/L-h) (Caldeira et al., 2020). It was reported that the maximum yield amounted to up to 190 g of ethanol per kg of apple pomace using an enzymatic pretreatment (Parmar & Rupasinghe, 2013).

Borujeni, Alavijeh et al. (2023) and Borujeni, Karimi et al. (2022) developed the conversion of apple pomace into bioethanol and bioproducts (pectin, chitin/chitosan, mycoproteins) by applying organosolv pretreatment (50% ethanol with 0.5 wt% acid, at 100°C) coupled with simultaneous saccharification and fermentation with fungi *Mucor indicus* (Figure 6.6).

Vaez et al. (2023) applied pretreatment of dried apple pomace with dilute sulfuric acid. Extraction of liquid fraction gave pectin and residues, which after AF produced bioethanol. Besides, the solid fraction after the pretreatment process was subjected to anaerobic fermentation to produce biogas. The highest yield for 1 ton of dried apple pomace was 164 kg of pectin, 99 L of bioethanol and 33.6 m^3 of biogas.

During AF and purification, waste is generated in the form of fermentation broths, stillage and residues after distillation. It consists of aqueous suspensions containing fruit solids, microorganisms and microbial debris. Currently, this waste is used as soil fertiliser with an impact on the environment (Mohana et al., 2009). However, the fermentation residues could also be used as feedstock in different bioprocesses to obtain other valuable products such as: biogas, surfactants or enzymes (Kharayat, 2012).

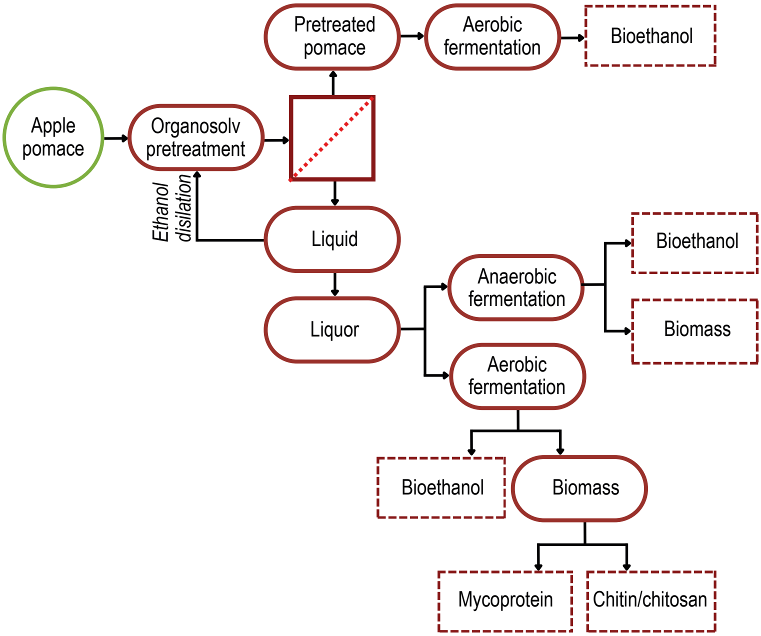

Figure 6.6. Conversion of apple pomace into bioethanol and bioproducts
Source: (Borujeni, Karimi et al., 2022).

6.3.5. Anaerobic fermentation (ANF)

ANF can be carried out from the remains of DF and the distillation process or directly after hydrolysation. The organic acids present in the fermented residue will be converted into biogas in the process of acetate- and methanogenesis. In the literature, there are some attempts to increase the energy efficiency of organic biomass by two-stage fermentation processes. Jung et al. (2022) have examined a two-stage system for the production of hydrogen and methane in mesophilic conditions from food waste. Chemical energy in feedstock was recovered up to 79% as renewable energy. In another study, the co-fermentation of garden/food waste was assessed in a two-stage process that combines hyperthermophilic DF and mesophilic ANF *(*Abreu et al., 2019*)*.

Biogas production by ANF is the most promising direction for the use of post-fermentation and distillation waste. However, due to the seasonal production of fruit waste, only co-digestion with another main feedstock can be used in commercial technology (Molinuevo-Salces et al., 2020).

Post-fermentation material is rich in nitrogen, phosphorus and organic matter and can be used as an organic fertiliser (Tambone et al., 2011) or as a soil conditioner (Tang et al., 2019). However, the digestate contains biodegradable organic residues and other contaminants. It could increase NH_3 emissions and induce environmental problems such as acidification and eutrophication (Rincon et al., 2019). Therefore, appropriate management of post-fermentation material is required before its safe discharge into the environment.

After separation, the liquid fraction (80–90% of the digestate total mass) rich in N and K can be used, e.g., for microalgae cultivation (Al-Mallahi & Ishii, 2022). The digestate solid (10–20% of the digestate total mass) is rich in C and P. There are some strategies to utilise it in value-added materials, such as: composting into biofertiliser (Du et al., 2018), pyrolysis in biochar (Kumar et al., 2021), hydrothermal carbonisation into hydrochar (Parmar & Ross, 2019) or solid-state fermentation into hydrolytic enzymes, biosurfactants and biopesticides (Cerda et al., 2019).

Conclusions

Sustainable management of fruit waste production is important to reduce the amount of food waste deposited in landfills and to develop strategies through their reuse for full valorisation and added economic value. According to the literature, fruit waste can be a good feedstock candidate for value-added chemicals and biofuel production in a biorefinery setting according to the circular economy.

In the food processing of fruit, depending on the quality of waste and the company's technological capabilities, the waste can be utilised directly or indirectly. The direct utilisation of fruit waste does not ensure full valorisation and does not fully minimise the environmental impact. The most sustainable management for the full valorisation of fruit waste, according to the circular economy, is the indirect utilisation, which requires an energy-intensive drying process before the biorefinery approach. However, there is still a long way to go for the cost-effective processes such as value-added phytochemicals extraction, biohydrogen and bioethanol production, which are in the early stages of research. Therefore, the above-presented biorefinery processes require a techno-economic analysis taking into account the type of biomass and its availability at the biorefinery site and throughout the production year.

References

Abreu, A. A., Tavares, F., Alves, M. M., Cavaleiro, A. J., & Pereira, M. A. (2019). Garden and food waste co-fermentation for biohydrogen and biomethane production in a two-step hyperthermophilic-mesophilic process. *Bioresource Technology*, *278*, 180–186. https://doi.org/10.1016/j.biortech.2019.01.085

Al-Mallahi, J., & Ishii, K. (2022). Attempts to alleviate inhibitory factors of anaerobic digestate for enhanced microalgae cultivation and nutrients removal: A review.

Journal *of Environmental Management*, *304*, 114266. https://doi.org/10.1016/j.jenvman.2021.114266

Azmir, J., Zaidul, I. S. M., Rahman, M. M., Sharif, K. M., Mohamed, A., Sahena, F., Jahurul, M. H. A., Ghafoor, K., Norulaini, N. A. N., & Omar, A. K. M. (2013). Techniques for extraction of bioactive compounds from plant materials: A review. *Journal of Food Engineering*, *117*(4), 426–436. https://doi.org/10.1016/j.jfoodeng.2013.01.014

Basak, B., Jeon, B. H., Kim, T. H., Lee, J. C., Chatterjee, P. K., & Lim, H. (2020). Dark fermentative hydrogen production from pretreated lignocellulosic biomass: Effects of inhibitory byproducts and recent trends in mitigation strategies. *Renewable and Sustainable Energy Reviews*, *133*, 110338. https://doi.org/10.1016/j.rser.2020.110338

Bayram, B., Ozkan, G., Kostka, T., Capanoglu, E., & Esatbeyoglu T. (2021). Valorization and application of fruit and vegetable wastes and by-products for food packaging materials. *Molecules*, *26*(13), 4031. https://doi.org/10.3390/molecules26134031

Borujeni, N. E., Alavijeh, M. K., Denayer, J. F. M., & Karimi, K. (2023). A novel integrated biorefinery approach for apple pomace valorization with significant socioeconomic benefits. *Renewable Energy*, *208*, 275–286. https://doi.org/10.1016/j.renene.2023.03.056

Borujeni, N. E., Karimi, K., Denayer, J. F. M., & Kumar, R. (2022). Apple pomace biorefinery for ethanol, mycoprotein, and value-added biochemicals production by *Mucor indicus*. *Energy*, *240*, 122469. https://doi.org/10.1016/j.energy.2021.122469

Caldeira, C., Vlysidis, A., Fiore, G., De Laurentiis, V., Vignali, G., & Sala, S. (2020). Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. *Bioresource Technology*, *312*, 123575. https://doi.org/10.1016/j.biortech.2020.123575

Cerda, A., Mejias, L., Rodriguez, P., Rodriguez, A., Artola, A., Font, X., Gea, T., & Sanchez, A. (2019). Valorisation of digestate from biowaste through solid-state fermentation to obtain value added bioproducts: A first approach. *Bioresource Technology*, *271*, 409–416. https://doi.org/10.1016/j.biortech.2018.09.131

Chemat, F., Vian, M. A., & Cravotto, G. (2012). Green extraction of natural products: Concept and principles. *International Journal of Molecular Sciences*, *13*(7), 8615–8627. https://doi.org/10.3390/ijms13078615

Choi, I. S., Lee, I. G., Khanal, S. K., Park, B. J., & Bae, H. J. (2015). A low-energy, cost-effective approach to fruit and citrus peel waste processing for bioethanol production. *Applied Energy*, *140*, 65–74. https://doi.org/10.1016/j.apenergy.2014.11.070

Costa, J. M., Ampese, L. C., Ziero, H. D. D., Sganzerla, W. G., & Forster-Carneiro, T. (2022). Apple pomace biorefinery: Integrated approaches for the production of bioenergy, biochemicals, and value-added products—an updated review. *Journal of Environmental Chemical Engineering*, *10*, 108358. https://doi.org/10.1016/j.jece.2022.108358

Cubero-Cardoso, J., Serrano, A., Trujillo-Reyes, A., Villa-Gómez, D., Borja, R., & Fermoso, F. (2020). Valorization options of strawberry extrudate agro-waste. A review. In A. de Barros & I. Gouvinhas (Eds.), *Innovation in the food sector through the valorization of food and agro-food by-products* (pp. 1–20). IntechOpen. https://doi.org/10.5772/intechopen.93997

Demiray, E., Kut, A., Karatay, S. E., & Dönmez, G. (2021). Usage of soluble soy protein on enzymatically hydrolysis of apple pomace for cost-efficient bioethanol production. *Fuel*, *289*, 119785. https://doi.org/10.1016/j.fuel.2020.119785

Doi, T., Matsumoto, H., Abe, J., & Morita, S. (2010). Application of rice rhizosphere microflora for hydrogen production from apple pomace. *International Journal of Hydrogen Energy*, *35*(14), 7369–7376. https://doi.org/10.1016/j.ijhydene.2010.04.173

Du, C., Abdullah, J. J., Greetham, D., Fu, D., Yu, M., Ren, L., Li, S., & Lu, D. (2018). Valorisation of food waste into biofertiliser and its field application. *Journal of Clean Production*, *187*, 273–284. https://doi.org/10.1016/j.jclepro.2018.03.211

Feng, X., Wang, H., Wang, Y., Wang, X., & Huang, J. (2010). Biohydrogen production from apple pomace by anaerobic fermentation with river sludge. *International Journal of Hydrogen Energy*, *35*(7), 3058–3064. https://doi.org/10.1016/j.ijhydene.2009.07.015

Górnaś, P., Rudzińska, M., Raczyk, M., Misina, I., Soliven, A., & Seglina, D. (2016). Composition of bioactive compounds in kernel oils recovered from sour cherry (Prunus cerasus L.) by-products: Impact of the cultivar on potential applications. *Industrial Crops and Products*, *82*, 44–50. https://doi.org/10.1016/j.indcrop.2015.12.010

Häkkinen, S., Heinonen, M., Kärenlampi, S., Mykkänen, H., Ruuskanen, J., & Törrönen, R. (1999). Screening of selected flavonoids and phenolic acids in 19 berries. *Food Research International*, *32*, 345–353.

Hay, J. X. W., Wu, T. Y., Juan, J. C., & Jahim, J. Md. (2013). Biohydrogen production through photo fermentation or dark fermentation using waste as a substrate: Overview, economics, and future prospects of hydrogen usage. *Biofuels, Bioproducts and Biorefining*, *7*(3), 334–352. https://doi.org/10.1002/bbb.1403

Hwang, J. H., Choi, J. A., Abou-Shanab, R. A. I., Min, B., Song, H., Kim, Y., Lee, E.S., & Jeon, B. H. (2011). Feasibility of hydrogen production from ripened fruits by a combined two-stage (dark/dark) fermentation system. *Bioresource Technology, 102*(2), 1051–1058. https://doi.org/10.1016/j.biortech.2010.08.047

Jung, J. H., Sim, Y. B., Ko, J., Park, S. Y., Kim, G. B. & Kim, S. H. (2022). Biohydrogen and biomethane production from food waste using a two-stage dynamic membrane bioreactor (DMBR) system. *Bioresource Technology*, *352*, 127094. https://doi.org/10.1016/j.biortech.2022.127094

Kharayat, Y. (2012). Distillery wastewater: Bioremediation approaches. *Journal of Integrative Environmental Science*, *9*(2), 69–91. https://doi.org/10.1080/1943815X.2012.688056

Koponen, J. M., Happonen, A. M., Mattila, P. H., & Torronen, A. R. (2007). Contents of anthocyanins and ellagitannins in selected foods consumed in Finland. *Journal of Agricultural and Food Chemistry*, *55*, 1612–1619.

Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P. L., Sawarkar, A. D., Singh, L., & Tsang, D. C. W. (2021). A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. *Journal of Cleaner Production*, *305*, 127143. https://doi.org/10.1016/j.jclepro.2021.127143

Kylli, P. (2011). *Berry phenolics: Isolation, analysis, identification and antioxidant properties*. [Unpublished doctoral thesis]. University of Helsinki.

Lau, K. Q., Sabran, M. R., & Shafie, S. R. (2021). Utilization of vegetable and fruit by-products as functional ingredients and food. *Frontiers in Nutrition*, *8*, 661693, https://doi.org/10.3389/fnut.2021.661693

Lipiński, A. J., Lipiński, S., & Kowalkowski, P. (2018). Utilization of post-production waste from fruit processing for energetic purposes: Analysis of Polish potential and case study. *Journal of Material Cycles Waste Management*, *20*, 1878–1883. https://doi.org/10.1007/s10163-018-0729-2

Maatta-Riihinen, K. R., Kamal-Eldin, A., Mattila, P. H., Gonzalez-Paramas, A. M., & Torronen, A. R. (2004). Distribution and contents of phenolic compounds in eighteen Scandinavian berry species. *Journal of Agricultural and Food Chemistry*, *52*, 4477–4486.

Magyar, M., da Costa Sousa, L., Jin, M., Sarks, C., & Balan, V. (2016). Conversion of apple pomace waste to ethanol at industrial relevant conditions. *Applied Microbiology and Biotechnology*, *100*, 7349–7358. https://doi.org/10.1007/s00253-016-7665-7

Martinez-Merino, V., Gil, M. J., & Cornejo, A. (2013). Biomass sources for hydrogen production. In L. M. Gandia, G. Arzamendi, & P. M. Dieguez (Eds.), *Renewable hydrogen technologies* (pp. 87–111). Elsevier.

Mirabella, N., Castellani, V., & Sala, S. (2014). Current options for the valorization of food manufacturing waste: A review. *Journal of Cleaner Production*, *65*, 28–41. https://doi.org/10.1016/j.jclepro.2013.10.051

Mohana, S., Acharya, B., & Madamwar, D. (2009). Distillery spent wash: Treatment technologies and potential applications. *Journal of Hazard Materials*, *163*(1), 12–25. https://doi.org/10.1016/j.jhazmat.2008.06.079

Molinuevo-Salces, B., Riaño, B., Hijosa-Valsero, M., González-García, I., Paniagua-García, A. I., Hernández, D., Garita-Cambronero, J., Díez-Antolínez, R. & María Cruz García-González, M. C. (2020). Valorization of apple pomaces for biofuel production: A biorefinery approach. *Biomass and Bioenergy*, *142*, 105785. https://doi.org/10.1016/j.biombioe.2020.105785

Nawirska, A. (2005). Binding of heavy metals to pomace fibers. *Food Chemistry*, *90*(3), 395–400. https://doi.org/10.1016/j.foodchem.2004.04.009

Nosecka, B. (red.). (2022). *Rynek owoców i warzyw. Stan i perspektywy*. Analizy Rynkowe. IERiGŻ PIB.

O'Shea, N., Ktenioudaki, A., Smyth, T. P., McLoughlin, P., Doran, L., Auty, M. A. E, Arendt, E., & Gallagher, E. (2015). Physicochemical assessment of two fruit by-products as functional ingredients: Apple and orange pomace. Journal *of Food Engineering*, *153*, 89–95. https://doi.org/10.1016/j.jfoodeng.2014.12.014

Ovcharova, T., Zlatanov, M., & Dimitrova, R. (2016). Chemical composition of seeds of four Bulgarian grape varieties. *Ciencia e Tecnica Vitivinicola*, *31*(1), 31–40. https://doi.org/10.1051/ctv/20163101031

Parmar, I., & Rupasinghe, H. P. V. (2013). Bio-conversion of apple pomace into ethanol and acetic acid: Enzymatic hydrolysis and fermentation. *Bioresource Technology*, *130*, 613–620. https://doi.org/10.1016/j.biortech.2012.12.084

Parmar, K. R., & Ross, A. B. (2019). Integration of hydrothermal carbonisation with anaerobic digestion. Opportunities for valorisation of digestate. *Energies*, *12*(9), 1586. https://doi.org/10.3390/en12091586

Pathak, P. D., Mandavgane, S. A., & Kulkarni, B. D. (2016). Valorization of banana peel: A biorefinery approach. *Reviews in Chemical Engineering*, *32*, 651–666. https://doi.org/10.1515/revce-2015-0063

Radojčin, M., Pavkov, I., Kovačević, B. D, Putnik, P., Wiktor, A., Stamenković, Z., Keševj, K., & Gere, A. (2021). Effect of selected drying methods and emerging drying intensification technologies on the quality of dried fruit: A review. *Processes*, *9*(1), 132. https://doi.org/10.3390/pr9010132

Redwood, M. D., Paterson-Beedle, M., & Macaskie, L. E. (2009). Integrating dark and light biohydrogen production strategies: towards the hydrogen economy. *Reviews in Environmental Science and Bio/Technology*, *8*, 149–185. https://doi.org/10.1007/s11157-008-9144-9

Reguengo, L., Salgaço, M., Sivieri, K., & Maróstica Jr, M. R. (2022). Agro-industrial by-products: Valuable sources of bioactive compounds. *Food Research International*, *152*, 110871. https://doi.org/10.1016/j.foodres.2021.110871

Reynoso-Camacho, R., Sotelo-González, A., Patino-Ortiz, P., Rocha-Guzmán, N., & Pérez-Ramírez, I. (2021). Berry by-products obtained from a decoction process are a rich source of low- and high-molecular weight extractable and non-extractable polyphenols. *Journal Food and Bioproducts Processing*, *127*, 371–387. https://doi.org/10.1016/j.fbp.2021.03.014

Rincon, C. A., De Guardia, A., Couvert, A., Le Roux, S., Soutrel, I., Daumoin, M., & Benoist, J. C. (2019). Chemical and odour characterisation of gas emissions released during composting of solid wastes and digestates. *Journal of Environmental Management*, *233*, 39–53. https://doi.org/10.1016/j.jenvman.2018.12.009

Rodriguez, G. S. L., & Raghavan, V. (2021). Green extraction techniques from fruit and vegetable waste to obtain bioactive compounds—a review. *Critical Reviews in Food Science and Nutrition*, *62*, 6446–6466. https://doi.org/10.1080/10408398.2021.1901651

Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. *Comprehensive Reviews in Food Science and Food Safety*, *17*, 512–531.

Tambone, F., Scaglia, B., Scotti, S., & Adani, F. (2011). Effects of biodrying process on municipal solid waste properties. *Bioresource Technology*, *102*(16), 7443–7450. https://doi.org/10.1016/j.biortech.2011.05.010

Tang, J., Li, X., Zhao, W., Wang, Y., Cui, P., Zeng, R. J., Yu, L., & Zhou, S. (2019). Electric field induces electron flow to simultaneously enhance the maturity of aerobic composting and mitigate greenhouse gas emissions. *Bioresource Technology*, *279*, 234–242. https://doi.org/10.1016/j.biortech.2019.01.140

Tao, Y., Zhang, Z., & Sun, D. W. (2014). Kinetic modelling of ultrasound-assisted extraction of phenolic compounds from grape marc: Influence of acoustic energy density and temperature. *Ultrasonics Sonochemistry*, *21*, 1461–1469. https://doi.org/10.1016/j.ultsonch.2014.01.029

Tian, Y., Puganen, A., Alakomi, H., Uusitupa, A., Saarela, M., & Yang, B. (2018). Antioxidative and antibacterial activities of aqueous ethanol extracts of berries, leaves, and branches of berry plants. *Food Research International*, *106*, 291–303.

Vaez, X., Karimi, K., Denayer, J. F. M., & Kumar, R. (2023). Evaluation of apple pomace biochemical transformation to biofuels and pectin through a sustainable biorefinery. *Biomass and Bioenergy*, *172*, 106757. https://doi.org/10.1016/j.biombioe.2023.106757

Vashisth, T., Singh, R. K. & Pegg, R. B. (2011). Effects of drying on the phenolics content and antioxidant activity of muscadine pomace. *LWT—Food Science and Technology*, *44*(7), 1649–1657. https://doi.org/10.1016/j.lwt.2011.02.011

Zhang, F., Wang, T., Wang, X. & Lü X. (2021). Apple pomace as a potential valuable resource for full-components utilization: A review. *Journal of Cleaner Production*, *329*, 129676. https://doi.org/10.1016/j.jclepro.2021.129676

Zhang, Q. W., Lin, L. G. & Ye, W. C. (2018). Techniques for extraction and isolation of natural products: A comprehensive review. *Chinese Medicine*, *13*, 20. https://doi.org/10.1186/s13020-018-0177-x