Ramesh C. Ray *Editor*

Fruits and Vegetable Wastes

Valorization to Bioproducts and Platform Chemicals

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Preface

The non-edible portion of fruits and vegetables after processing (waste), such as peels, pods, seeds, and skins, accounts for about 10–50% of the total weight of the fresh produce. Fruit-processing industries alone contribute more than 0.5 billion tons of waste worldwide. Such wastes pose increasing disposal and potentially severe environmental pollution problems and represent a loss of valuable biomass and nutrients. Most of these wastes are dumped in landfills, used as animal feeds, or burned as an alternative. Fruits and vegetable wastes (FVWs) usually have a composition of sugar, starch, proteins, phenolic phytochemicals, and minerals; therefore, they should not be considered "wastes" but as raw materials for other industrial processes. FVWs are thus a particular group of solid waste (biomass) that needs to be characterized to understand the nature of applications as raw materials and propose an appropriate methodology for bioprocessing into value-added commodities. FVWs provide conditions amenable for microorganism growth, which opens up great opportunities for their reuse in fermentation processes. FVWs can be used as the solid support, carbon, and nutrient sources in fermentation to produce a variety of value-added biocommodities such as enzymes, single-cell proteins, and biocomposites, phenolic bioactive compounds, aroma and flavor compounds, and platform chemicals like organic acids, bioethanol, biobutanol, and fluorescent carbon-dots. This book deals with all these aspects of valorization of FVWs into different biocommodities and platform chemicals using primarily fermentation processes in the form of 18 chapters.

The book is broadly divided into five parts: (1) introduction, dealing with overall food loss in fruits and vegetables worldwide and issues and resources; (2) bioactive compounds in FVWs and their extraction methods; (3) mushrooms, livestock feeds, and composts, based on FVWs; (4) enzymes, biofuels, and other bio-based commodities such as biocomposites, oligosaccharides, sugar alcohols, and fluorescent carbon dots; and (5) life-cycle analysis. The individual chapters are written by authors from different countries specialized in FVW valorization research. Practical and commercial applications of the technologies are cited in these chapters wherever information is available.

The book provides up-to-date information on research and development in the field of valorization of FVWs. The editor is immensely thankful to the authors for their full cooperation and timely submission of manuscripts.

Bhubaneswar, India Ramesh C. Ray

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Part I
Introduction

Chapter 1
Overview of Food Loss and Waste in Fruits and Vegetables: From Issue to Resources

Victoria Bancal and Ramesh C. Ray

Abstract Vegetables and fruits contain many phytochemicals, vitamins and minerals, and dietary fibers that are good for human health. However, on a global scale, a substantial amount (25–50%) of fruits and vegetables is lost from farm to fork, together called post-harvest losses. These losses represent both food security and environmental issue and therefore counteract any effort to build sustainable food systems since they deprive populations of a considerable amount of healthy food and represent a huge waste of resources. A significant obstacle in achieving mitigation of post-harvest losses is the lack of precise knowledge of the actual magnitudes of losses, which makes it impossible to measure progress against any loss reduction targets. After a brief historical sight on how science addressed the issue, this chapter will present the concepts and definitions of fruits and vegetables food loss and waste and finally review the state of knowledge about the magnitude, distribution in the food supply chain, and main causes of fruits and vegetables food loss and waste for this category of products.

Keywords Fruits · Vegetables · Food loss and waste · Food Loss Index · Post-harvest · Phytochemicals · Vitamins

1 Introduction

Vegetables and fruits contain many phytochemicals, vitamins, and minerals, dietary fibers that are good for human health. Vitamins A (carotene), C, and E, magnesium, zinc, phosphorus, and folic acid are some of the essential constituents. For example, homocysteine, a chemical that may be a risk factor for coronary heart disease, is reduced by folic acid. Fruits and vegetables are also low in fat, salt, and sugar.

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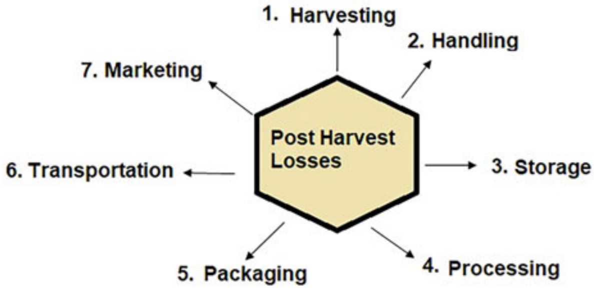

Fig. 1.1 Different stages of post-harvest losses of horticultural commodities

Therefore, a high intake of fruits and vegetables, as part of a well-balanced regular diet and a healthy, active lifestyle, can reduce obesity, lower blood cholesterol, and lower blood pressure. According to the UN's Food and Agricultural Organization (FAO) data, the global fruit production was about 870 million metric tons (MMT) in 2018. Banana production (116.78 MMT) was the highest, followed by watermelon (100.41MMT), apple (87.23 MMT), and orange (78.7 MMT) (https://www.statista.com/statistics/264001/worldwide-production-of-fruit-by-variety/). Vegetables are harvested in vast quantities all over the world—more than one billion metric tons each year. For example, over 834 MMT of fresh vegetables are produced in Asia (https://www.statista.com/statistics/264662/top-producers-of-fresh-vegetables-worldwide/). Tomatoes are the most popular vegetable globally in terms of production volume. However, a substantial amount (25–50%) of fruits and vegetables is lost along the supply chain, together called post-harvest losses (PHL). In horticultural commodities, the PHL can be divided into seven stages: harvesting, handling, storage, processing, packaging, transportation, and marketing (Fig. 1.1). Post-harvest losses are a waste of resources such as land, water, energy, and inputs utilized in production.

The inaugural World Food Conference in 1974 sparked interest in PHL to achieve a 50% reduction by 1985 (Parfitt et al. 2010). There is, however, no account of progress toward the 1985 PHL reduction target. A key barrier to PHL mitigation is the absence of a precise understanding of the real magnitudes of losses, which makes it impossible to monitor success against any loss reduction targets. The focus was initially on reducing grain losses, but by the early 1990s, it had expanded to include roots and tubers and fresh fruits and vegetables.

2 Food Wastes: Concept and Definitions

The Food and Agriculture Organization (FAO) published a report in 2011 titled "Global Food Losses and Waste: Extent, Causes, and Prevention." This widely mediatized study brought a renewed interest in the theme of food losses and waste, considered a sustainable means to improve food security, reduce the pressure on natural resources, and combat climate change. In that way, despite methodological issues, it constituted a trigger for public and private initiatives. The year 2014 was even chosen as the European Year against food loss and waste, and the EU set a target of halving wasted quantities by 2025 (Redlingshöfer and Soyeux 2011).

2.1 A Historical Sight on the Issue of Food Loss and Waste

The World Food Conference in 1974 launched the "Prevention of Food Losses" program, which drew international attention to post-harvest losses (Grolleaud 2002). From that point to the 1980s, research focused mainly on grain storage in rural areas. This trend of reducing post-harvest losses to a single category of plants (cereals) and insect damage was explained because it was mainly the work of entomologists (Guillou and Matheron 2011), and the current FAO's objective to promote policies aimed at improving food availability. Not until the 1990s, that field was extended to roots, tubers, and fruits and vegetables (Parfitt et al. 2010). Definition grew more complex, introducing a distinction between quantitative and qualitative loss (Grolleaud 2002), and measurement and estimation methods were improved by Compton et al. (1998), Pantenius (1988), Compton and Sherigton (1999), and La Gra et al. (2016). But from this period, food losses seem to be forgotten.

The 2008 price hike and the awareness of the major changes that await food systems (demographic challenge, climate change, extreme events, resource depletion, etc.) generated renewed interest in food security issues (Esnouf and Huyghe 2015). The disappointing levels of adoption of new technologies led to prioritizing the identification of factors, causes, and conditions of losses throughout the post-harvest chains (Parfitt et al. 2010). The publication of the FAO (2011) report triggered many public and private initiatives as food loss and waste (FLW) reduction was presented as a sustainable means to improve food security, reduce the pressure on natural resources, and combat climate change (Lundqvist et al. 2008; FAO 2011). International attention is now firmly reflected in the 2030 Agenda for Sustainable Development Goal (SDG) and Target 12.3, calling for the halving 2030 of per capita global food losses. The year 2014 was even chosen as the European Year against food loss and waste (Redlingshöfer and Soyeux 2011).

2.2 Definition of Food Loss and Waste Depends on the Issue Targeted

Although the concept of food loss or waste may appear to be straightforward, there is no universally accepted definition of food loss and waste in practice. Despite efforts for standardization, several definitions remain and are used by authors. For this reason, comparison, aggregation, and analysis of data from different sources present methodological issues. For example, Chaboud and Daviron (2017) illustrated that the scope, timing, terminology, and criteria defining FLW are deeply related to the perspectives or issues that stakeholders focus on. They identified two main ways to address FLW: food security issues or food system efficiency and resource use issues.

2.2.1 Food Loss and Waste (FLW) Definition from a Food Security Perspective

The 2011 FAO report defined FLW as *"the reduction, at all stages of the food chain, that is to say from the time of harvest to that of consumption of the mass of edible foods originally intended for human consumption, whatever the cause*" (FAO 2011), introducing the concept of waste, considering FLW from the moment products are ready for harvest (i.e., not just post-harvest) and food not consumed and redirected to alternative uses included as FLW (Chaboud and Daviron 2017). However, in 2019, with the launch of two new indicators that are the **Food Loss Index and the Food Waste Index**, FAO used a slightly different definition:

- **Food loss** is "*the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retail, food service providers, and consumers. Thus, food loss refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption.*"
- **Food waste** is "*the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food services, and consumers. Food waste refers to food appropriate for human consumption being discarded, whether or not it is kept beyond its expiry date or left to spoil.*"
- **Quantitative FLW** (also called physical FLW) is "*the decrease in the mass of food destined for human consumption as it is removed from the food supply chain.*"
- **Qualitative FLW** refers to "*the decrease in food attributes that reduces its value in terms of intended use. It can result in reduced nutritional value (*e.g.*, smaller amounts of vitamin C in bruised fruits) and/or the economic value of food because of non-compliance with quality standards. In addition, a reduction in quality may result in unsafe food, presenting risks to consumers' health.*"
- **Products nonintended to human consumption and inedible parts** of food are not considered food and therefore are not included in FLW.
- **The fate of discarded food**: Food diverted to productive nonfood use (as feed or biofuel use) retains part of its value and is not considered loss or waste. Food that ends up in this waste management process (as anaerobic digestion) is included in FLW (FAO 2019).

2.2.2 Food Waste Definition from a Resource Management Perspective

A second definition appears within the framework adopted by the European Commission and the Food Use for Social Innovation by Optimising Waste Prevention Strategies (FUSIONS) program and puts the issue of post-harvest loss reduction on the perspective of resource management and environment (FUSIONS 2014). FUSIONS framework uses the unique terminology "waste," whatever the cause or stage of the chain. There is no distinction between edible and nonedible parts of an agricultural product. Foods redirected toward animal feed and industry (biomaterials, biorefinery) are described as upgrades or conversions and are not counted as waste. This waste-oriented approach aims to reduce waste of all kinds and limit the negative impacts and costs associated with the treatment of food and nonfood. It often considers the local environmental impact and calls for questioning the fate of waste that can be used as feed, recycled, or produce energy or compost, incinerated or disposed of in a landfill (HPLE. 2014; Chaboud and Daviron 2017).

In the EC framework, "*food waste is any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed of (including composted, crops ploughed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea*)."

2.3 What Are the Expected Benefits of Saving Foods?

Feeding over 9.1 billion people with safe food by 2050 is the key challenge for agricultural research, development, and policy (Parfitt et al. 2010). Consequently, food production is expected to increase by 70% to meet the worldwide food supply needs by 2050. It is also forecasted that a growing population and rising incomes will increase demand for agricultural products by 35–50% between 2012 and 2050, exerting even more pressure on natural resources (FAO 2019). Increasing the efficiency of the food system, improving food security and nutrition, and contributing to environmental sustainability are all viewed as significant reasons to minimize FLW (FAO 2019).

2.3.1 Contribute Toward Environmental Sustainability

Three major types of environmental footprints of FLW are generally quantifiable:

- GHG (greenhouse gases) emissions (**carbon footprint**).
- Pressure on land (**land footprint**).
- Pressure on water resources (**water footprint**).

FAO calculated the impact of food waste on natural resources, including its carbon footprint, estimated at 3.6 GtCO2 (total annual anthropogenic GHG emissions) eq, excluding the 0.8 GtCO2 eq of deforestation managed organic soils. This represents about 8% of total anthropogenic GHG emissions. The two other dimensions are addressed by Kummu et al. (2012) that estimated 23% of total global cropland area, 23% of total global fertilizer use, and 24% of total freshwater resources used in food crop production (27 m^3/cap/yr) are dedicated to the production of food is lost or wasted.

Food production is resource-intensive and has substantial environmental consequences from an environmental standpoint. FLW, therefore, represents a huge waste of resources, some of them being nonrenewable. It appears to be a waste of natural resources as well as a squandered opportunity to feed the world's expanding population.

2.3.2 Improve Food Security and Nutrition

Considerable attention has been directed toward increasing food production, which, to provide enough qualitative food to humankind in 2050, should increase by 50–70%. However, on a limited planet, an essential and complementary factor often forgotten is reducing food loss and food wastes (Hodges et al. 2011). Plus, consumers expect food quality and safety across the food supply chain (FSC). FLW occurs at all stages of FSC, primary factors involved in part of their expected revenue and reducing access and availability of food products for consumers. FAO (2011) established that between 208 and 300 kg of food per capita in European and North American countries and 120–170 kg of food per capita in sub-Saharan Africa and South and Southeast Asia are lost or wasted throughout the food chain each year. According to Kummu et al. (2010), around one-quarter of food (614 kcal/cap/day) is lost in the FSC, while almost half of the losses might be avoided with a more efficient supply chain. If food crop losses could be cut in half, one billion more people could be nourished (Kummu et al. 2012).
However, food security is not obtained by a sufficient intake of calories. An unbalanced diet can lead to nutritional deficiencies, affecting the health of vulnerable populations. Therefore, a balanced and healthy diet is required to reach food security. Aside from grains, a variety of fruits, vegetables, root, and tuber crops also contribute significantly to the nutrition and income of millions of people in developing countries. However, these crops incur considerable losses (Akande and Diei-Ouadi 2010; Kitinoja et al. 2011; Lore et al. 2005).

Reducing FLW in fruits and vegetables might contribute to food security by diversifying food intakes and balancing the diet providing key nutritional components such as vitamins and minerals. Yet commodities in these categories have been neglected in past post-harvest studies (Affognon et al. 2015).

2.4 Fruits and Vegetables Have Been Neglected by Post-Harvest Loss (PHL) Researchers

Affognon et al. (2015), reviewing the state of current PHLs in sub-Saharan Africa, showed that global data on FLW are often based on old studies (over 30 years old), partial (focused on storage, and cereals), and obsolete if not untraceable. Kitinoja and Kader (2015) also highlighted the information gaps for fruits and vegetables, stating that missing data and insufficient comprehensive measurements along the entire value chain, as well as reporting on all three aspects of loss, that is, physical, quality, and economic losses, exist for regions, countries, and critical crops. This lack of relevant information about the true extent of loss makes it impossible to measure progress. However, a considerable number of the studies were completed after 2000, indicating a growing interest in PHL research and development (Affognon et al. 2015; Delgado et al. 2017, 2019).

PHLs were primarily gathered by surveys/interviews or sampling/direct measurements (Magalhaes et al. 2021). A case study by Blond (1984), cited in Kitinoja and Kader 2015), shows the importance of the methods. Physical losses of potatoes, grapes, and tomatoes were 17.6%, 28.0%, and 43.2%, respectively, in Egyptian farms and wholesale and retail marketplaces. However, when these same value chain stakeholders were interviewed, they reported average total losses of 8.8, 11.9, and 27.6%, demonstrating that their perceptions of losses were significantly lower than reality. These widely dispersed studies' estimations of PHLs for horticulture crops vary slightly and differ by region, country, harvest, and season, with little explanation of what is assessed, when, or how. It results that in literature, estimates of PHL magnitudes in fruits and vegetables vary widely, from 10% to 70% of the production.

3 Overview of Fruits and Vegetables Loss and Waste

Depending on the commodity, global food losses have been estimated to be in the range of 25%–50% of production quantities, caloric content, and/or market value (Lipinski et al. 2013; FAO 2011).

3.1 Global Data on Fruit and Vegetable Food Loss and Waste

According to some studies, global annual losses and wastage amount to roughly 35% of initial production, or 1.3 billion tonnes of food destined for human consumption (FAO 2011). Fruits and vegetables (together with root and tuber crops) are particularly perishable. Hence substantial losses are unsurprising, especially in areas with poor postproduction infrastructure for managing perishable produces

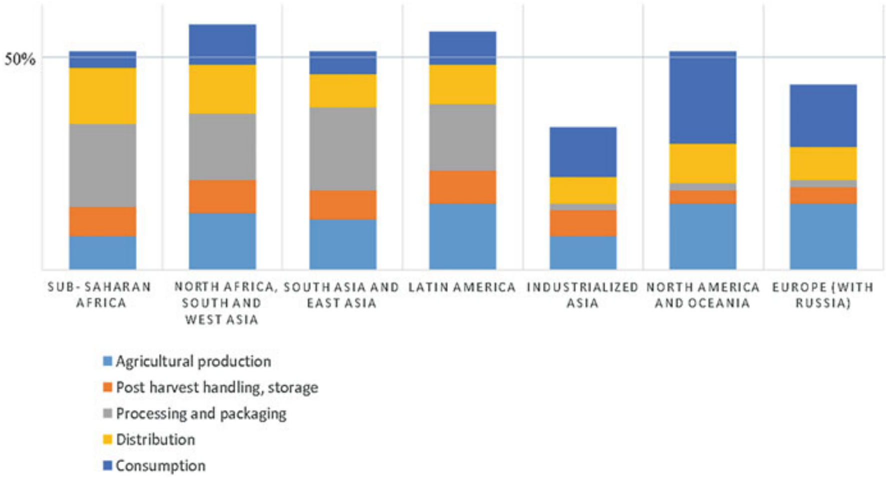

Fig. 1.2 Initial production of fruits and vegetable loss or waste per region and stages of the supply chain (FAO 2011)

(Affognon et al. 2015; FAO 2019). Many international authorities and journal article authors typically quote a general range of 30–50% post-harvest losses. FAO (Food and Agriculture Organization) (2011) currently uses 45% for global losses of both roots/tuber crops and fruits/vegetables (Kitinoja and Kader 2002, 2015). In South Africa, for example, fruit and vegetables, along with roots and tubers, account for 57% of total food waste, whereas fish, seafood, and meat account for only 6% (Diei-Ouadi and Mgawe 2011; Ooelofse and Nahman 2012). Each year, 12 million tonnes of fruits and 21 million tonnes of vegetables are lost in India, according to the Food Corporation of India. Meta-analyses from Xue et al. (2017) and Fabi et al. (2021) concur within the broader amplitude of losses for fruits and vegetables above other groups. Still, the Food Loss Index (FLI) established lower figures, and fruits and vegetables were the second group with a higher level of food losses (22% of production lost) after roots and tubers (25% of production lost) from harvest to distribution (FAO 2019). Since FLI calculation excludes retail and consumer stages, these figures, compared to the study from 2011, show the large contribution of the last steps (retail and consumption) of the supply chain to FLW of fruits and vegetables.

From FAO (2011) (Fig. 1.2, Table 1.1), it is interesting that reported losses and wastes for fruits and vegetables are high in both industrialized and developing countries. However, different patterns in the distribution of loss and waste can be noted. In developing countries, losses in the initial steps of the supply chains tend to be higher than in the last stages. On the other hand, in developed countries, wastes are at the consumer level for all commodities are way more important. The results presented by region also offer evidence of the extent of the higher losses in low-income countries (subtracting consumer wastes). For fruits and vegetables, median losses are estimated to be higher than 10% in Africa and Latin America.

Table 1.1 Distribution of food loss and wastes along fruits and vegetables supply chains

Region	Agricultural production	Post-harvest, handling and storage	Processing and packaging	Distribution	Consumption
Sub-Saharan Africa	10%	9%	25%	17%	5%
North Africa, South and West Asia	17%	10%	20%	15%	12%
South Asia and East Asia	15%	9%	25%	10%	7%
Latin America	20%	10%	20%	12%	10%
Industrialized Asia	10%	8%	2%	8%	15%
North America and Oceania	20%	4%	2%	12%	28%
Europe (with Russia)	20%	5%	2%	10%	19%

Source: Based on FAO (2011) data

In comparison, they range between 4% and 7% in Europe and North America at retail (Fabi et al. 2021). For example, in the United Kingdom, fruit wastage was estimated at 55% of the overall production, 37% at the consumer level. On the other hand, in Rwanda, tomato losses reached 49% of the production, but only 5% were due to consumer behavior. In comparison, 21% of wastage occurred at the production stage and 11.5% at transport and retail (FAO 2019).

3.2 *Fruits and Vegetables Food Loss and Wastes Are Highly Contact and Supply Chain-Related*

Regarding the specific group of foods, the magnitude of FLW varies concerning the region, country, crop, and season. Apart from the development level, the distribution of food losses differs from one region to another. Losses are highest in sub-Saharan Africa. Observations report 15–50% fruits and vegetables on-farm losses (FAO 2019). This very broad range of observations highlights the need to measure losses carefully for specific value chains to identify concretely where significant losses occur (FAO 2019). All regions showed between 0 and 15% of fruits and vegetables are wasted at the retail level, except sub-Saharan Africa, where waste levels can reach up to 35% (excluding outliers), indicating a significant potential for waste reduction in this region (FAO 2019). Northern America and Europe have the lowest percentage of fruits and vegetables wasted at the retail level. However, it is still large (3.75%), and losses exceed 10%, corroborating the findings of high levels of retail waste in high-income countries. Eastern and Southern Asia suffer the highest loss level (around 38%) (Papargyropoulou et al. 2014).

This regional variation could be explained in part by a variety of factors in the literature, all of which are highly context and crop-dependent. Also, the previous assumptions on the highest level of losses in developing countries and their distribution mainly at the initial supply chain stages are verified in many cases. In that case, they can't be generalized (Cappellini and Ceponis 1984).

FLW levels were lower than the 30–50% indicated by Chaboud and Moustier (2021), who analyzed the distribution of tomato losses and waste in Colombia. Fresh produce was reported at the production and post-harvest stages in poor and middle-income nations by the FLW range (FAO 2011; Parfitt et al. 2010). The average percentage FLW across the entire food chain was 13% at the farm level, a little over 1% at the trader level, and 3–4% at the retail level. In the FSC as a whole, the average cumulative percentage FLW was 15–20%. This was owing to a variety of consumer preferences and the relatively high acceptability of substandard produce, a shorter harvest-to-sale time, a variety of marketing strategies used to sell downgraded and damaged products, and the overlap and complementarity of the supermarket and nonsupermarket channels. The authors also mentioned the relatively favorable agroclimatic and infrastructural conditions that characterized the case study. In India, Kitinoja et al. (2019) also found relatively low quantitative losses in the tomato supply chain, with an average of 14% of losses from farm to retail.

The case of cassava also illustrates the difficulty of pulling a general conclusion on the distribution and causes of losses for a specific commodity. Naziri et al. (2014) assessed the extent of physical (quantitative) and economic (qualitative) losses at different stages of cassava value chains in four countries: Ghana, Nigeria, Vietnam, and Thailand. The results showed that the cultural practices and level of infrastructure, processing, industrialization, and consumption patterns could make a significant difference (Table 1.2). Ghana incurred a higher rate of physical loss (12.4%), followed by Vietnam (6.7%). But Vietnam was first and Ghana second regarding the volume of roots affected by economic losses. Finally, in monetary value, losses were ten times higher (500 million USD) in Ghana than in any other region, mostly related to physical losses. The most industrialized country, Thailand, had the highest percentage of loss at the harvesting stage of cassava due to unnoticed roots and breakages related to mechanized harvesting, while manual harvesting and gleaning limit losses in the three other regions. In Ghana, cassava roots are transported fresh over considerable distances because processing is a household activity leading to a high level of post-harvest deterioration and losses at transport and retail. Nevertheless, losses at processing can still be substantial, and it appears that they affect the traditional processing sub-chains (*Gari* in Nigeria and chips in Thailand and Vietnam).

This example illustrates the type of loss assessed and how to present them. Instead of absolute (kg) or relative (% of production), value or volume unit against monetary value may affect the interpretation globally.

Fruits and vegetables also incur substantial monetary value losses—when their quality deteriorates. Volumes ranging from 4.8 to 81% at farm level, 5.4–90% at the wholesale level, and 7–79% at retail level suffer damage, spoilage, or decay, resulting in economic value losses estimated at 16–40% for various fruits and

Table 1.2 Distribution of losses in cassava value chains

	Losses by stage (%)				Total losses at national scale		
Country	Harvest	Trading, transport, and handling	Processing	Retail and consumption	Total physical losses (t)	Total physical loss (% of national production)	Value of economic losses (million USD)
Ghana	2%	6%	17%	**76%**	**1,752,287**	12.4%	520
Nigeria	12%	6%	**82%**	0%	481,258	6.7%	50
Thailand	**70%**	0,4%	0,4%	29%	500,424	2.5%	50
Vietnam	7%	18%	**73%**	2%	304,893	3.1%	35

Source: Naziri et al. (2014)

vegetables (tomato, amaranth, okra, oranges, mango (Kitinoja and Cantwell 2010; Kitinoja and Al Hassan 2012). For example, in Niger, 15% of dried onions and potatoes were discarded (physical losses), but on the rest, 65% ended sold at a lower price due to low product quality (Tröger et al. 2007). The same situation was observed in Kenya, where 30–50% of dessert bananas were sold at a reduced market value (for 11, 2% physical losses) (Save food. 2014).

Food quality degradation can lead to nutrient degradation and bio-contamination, resulting in a loss of food value and the emergence of food-borne health risks. Poor processing, preservation, and storage technologies were partly responsible for the significant losses of micronutrients (Kitinoja and Kader (2002, 2015).

Table 1.3 summarizes results from previous researches on the extent of food losses in fruits and vegetables in different parts of the world. From this, it appears that most of the research data on fruits and vegetables food loss and waste refer to a few species. Potatoes, cabbage, onions, and tomatoes have been the most extensively researched vegetables, followed by a few fruit crops (mango, dessert banana, oranges, among others). Percent losses are sometimes given as averages of several or many crops (Fehr and Romao 2001; Underhill and Kumar 2014) or averages for a single crop across multiple countries (Fehr and Romao 2001; Underhill and Kumar 2014) (Weinberger et al. 2008).

Overall, we can be disappointed that the levels of reported losses for fruits and vegetables worldwide do not appear to have altered much since the 1970s, based on estimates of 30–40% losses published by the National Academy of Sciences in the United States.

4 Causes of FLW in Fruits and Vegetables

The causes of FLW are numerous and vary according to the stages of the food supply chain, the regions studied, and the food product under consideration (Gauraha 1999; Magalhaes et al. 2021).

4.1 Perishability of Fruits and Vegetables Partly Explains Their High Level of Loss and Waste Among Other Food Products

The main cause of post-harvest loss of fruits and vegetables is their high to very high perishability. Fruits and vegetables usually travel through the supply chain as fresh, unprocessed products. They continue to metabolize and consume their nutrients throughout their shelf life, from harvest through packing, distribution, marketing, and sale (Ray and Ravi 2005; Tomlin et al. 2010). Respiration, enzymatic breakdown, and microbial populations actively contribute to the degradations of

Table 1.3 Level of food losses in fruits and vegetables from literature

Region and country	Commodity	Method used	Losses	Reference
Sub-Saharan Africa				
Benin	Tomato	Sampling	28% in volume; 40% in economic value in 5 days	IITA (2008)
Benin	Tomato		23% at handling and storage, 31.3% at marketing (re-sorting)	Kitinoja et al. (2011)
	Leafy vegetables		17.3% losses at handling and storage, 31% at marketing (re-sorting)	
Benin	Lettuce		Lettuce: 36% at production, 22% at wholesale, 9% at retail	Kitinoja et al. (2011)
	Tomato		Tomato: 13% at production, 8% at wholesale, 12% at retail	
Benin	Mango		17–73% losses at harvest	Vayssieres et al. (2008)
Cameroun	Cassava	Survey and sampling	Gari supply chain: 40.4% Cassava stick supply chain: 37.7%	FAO (2018)
Cameroun	Tomato	Survey and sampling	33.8% (with 28.3% only pre-harvest and harvest and 5.5% at transport)	FAO (2018)
Cameroun	Potato	Survey and sampling	45.90% (34% in pre-harvest and harvest stage; 9% storage, 2.8% at retail)	FAO (2018)
Ghana	Tomato	Interviews	20%	Bani et al. (2006)
Ghana	Tomato	Sampling	25% (farm); 21.5% (wholesale); 23% (retail) physical losses	WFLO (2010)
Ghana	Yams	Sampling	25–63% price discount depending on degree of quality losses	Bancroft et al. (1998)
Kenya	Banana (imported from Uganda)	Sampling	18.2–45.8%	George and Mwangangi (1994)
Kenya	Dessert banana and plantains	Survey and sampling	11.2% physical losses; 30–50% reduced market value 4.6% physical losses; 20–30% reduced market value	Save Food (2014)

(continued)

Table 1.3 (continued)

Region and country	Commodity	Method used	Losses	Reference
Niger	Dried onions and tomatoes	Sampling	15% discarded; 65% sold with high levels of quality losses	Tröger et al. (2007)
Nigeria	Tomato	CSAM (survey)	10–40% from the farm to the retail market (15.2% average)	Kitinoja et al. (2019)
Nigeria	Tomato Bell pepper Hot pepper	Survey	20% (farm); 28% (transit) 12% (farm); 15% (transit) 8% (farm); 10% (transit)	Olayemi et al. (2010)
Nigeria	Yam	Survey	12.4% (economic loss = 10.5%)	Okah (1997)
Rwanda	Tomato	Commodity system assessment methodology (survey)	50–60%. From the farm to the retail market (18.3% average)	Kitinoja et al. (2019)
Rwanda	Tomato	Sampling	7.8% (farm); 10.7% (wholesale); 14.7% (retail) physical losses	WFLO (2010)
Tanzania	Sweet potato	Sampling	32.5–35.8%	Rees et al. (2001)
Tanzania	Sweet potato	Sampling	86% damaged (post-harvest handling and transport) 9% loss of market value	Tomlins et al. (2000)
Tanzania	Sweet potato		23.7–66.9%	Tomlins et al. (2007)
Tanzania	Fruits	Survey	0–33% physical loss; 5–80% of traded fruits suffering from quality loss	Ohiokpehai et al. (2009)
Tanzania	Vegetables	Survey	0.4–35% physical loss; 0.5–60% of traded vegetables suffering for quality loss	Ohiokpehai et al. (2009)
South Africa	Grapes	Sampling	Physical loss: 5.9–13.9% at farm, storage: 2.4–7.4% at storage, 3.6% at retail, 4.4% at export. Economic impact: 17 million USD/year	Ooelofse and Nahman. (2012) and Blanckenberg et al. (2021)
Asia				
Cambodia Laos Vietnam	Tomato	Survey	24.6% 16.9% 19.1%	Weinberger et al. (2008)

(continued)

Table 1.3 (continued)

Region and country	Commodity	Method used	Losses	Reference
Cambodia Laos	Yard-long bean	Survey	21.8% 12.2%	Weinberger et al. (2008)
Laos Vietnam	Chili pepper	Survey	10.7% 16.9%	Weinberger et al. (2008)
Fiji	Fruits and vegetables	Sampling	0.07–2.44% 4.07–10% In municipal markets	Weinberger et al. (2008)
Bangladesh	Fruits and vegetables	Survey	23.6–43.5%	Kamrul Hassan et al. (2010)
Bangladesh	Litchi	Survey	8% at harvest 4.6% during handling 7.5% by consumer	Molla et al. (2010)
India	Tomato	Commodity system assessment methodology (survey)	1–18% from the farm to the retail market (14% average)	Kumar et al. (2006); Kitinoja et al. (2019)
India	Potato	Sampling Sampling	29.4% (16.2% economic loss) 10.5%	Ajay and Singh (2004); Pandey et al. (2003); Kumar et al. (2004) Kumar et al. (2006)
India	Onion	Sampling Sampling	12.9% 15.7%	Ajay et al. (2003); Kumar et al. (2006) Chaugule et al. 2004)
India	Tomato	Sampling Interview Sampling	11.0–21.4% 35% 1% economic loss	Pal et al. (2002); Sharma et al. (2005) Gajbhiye et al. (2008) WFLO (2010)
India	Cauliflower and cabbage	Interviews	15–20% 15–20%	Pal et al. (2002); Gajbhiye et al. (2008)
India	Curcurbits	Sampling	52% economic loss	WFLO (2010)
India	Bell pepper	Sampling	6.7–17.1	Sharma et al. (2005)
India	Mango	Sampling	20% economic loss	WFLO (2010)
India	Okra	Sampling	20% economic loss	WFLO (2010)
India	Litchi	Sampling	30% economic loss	WFLO (2010)
India	Banana	Sampling	28.8% (wholesale); 18.3% (cooperative)	WFLO (2010)
Nepal	Cauliflower, cabbage, and tomato		47%: 6% (farm), 41% (retail), 43%: 9% (farm), 34% (retail) 10%: 3% (farm), 7% (retail)	Udas et al. (2005)

(continued)

Table 1.3 (continued)

Region and country	Commodity	Method used	Losses	Reference
Pakistan	Tomato, potato, and onion	Survey	20% 22, 12.9%	Mujib-Ur-Rehman et al. (2007) Zulfiqar et al. (2005)
Pakistan	Mango	Survey	20–30%	Mushtaq et al. (2005)
Sri Lanka	Bananas	Survey	20% from farm gate to retailer	Wasala et al. (2014)
Sri Lanka	Tomato	Survey	54% cumulative (measured at wholesale market)	Rupasinge et al. (1991)
Thailand	Cabbage and leaf lettuce	Sampling	28–32% 50–60%	Boonyakiat (1999)
North Africa/Middle East				
Egypt	Oranges and tomatoes	Sampling	14% 15%	El-Shazly et al. (2009)
Iran	Grapes	Survey	13%	Jowkar et al. (2005)
Jordan	Tomato, eggplant, pepper, and squash	Sampling	18% (tomato), 19.4% (eggplant), 23% (pepper), 21.9% (squash)	El-Assi (2002)
Oman	Fresh produce	Survey	3–19%	Opara (2003)
Saudi Arabia	Tomato, cucumber, figs, grapes, and dates	Survey	17% (tomato), 21.3% (cucumber), 19.8% (figs), 15.9% to 22.8% (grapes), 15% (dates)	Al-Kahtani and Kaleefah (2011)
Latin America				
Brazil	Tomato, bell pepper, and carrot	Interviews	30% 30% 12%	Vilela et al. (2003)
Brazil	Pineapple, banana, orange, papaya, and passion fruit	Sampling	Total 19.3%: 11.6% (wholesale), 7.7% (retail)	Kitinoja and Kader (2015)
Brazil	Fruits and vegetables	Interviews	16.6% (marketing chain); 3.4% (consumer)	Fehr and Romao (2001)
Colombia (Cali)	Tomato	Interviews	Cumulative average of unsold tomato: 15–20%; 13% at farm, 1% for traders, 3–4% at retail	Chaboud and Moustier (2021)

Adapted from Kitinoja and Kadar (2015), Blanckenberg et al. (2021), Chaboud and Moustier (2021)

Table 1.4 Food losses versus perishability of fruits and vegetables

Crops	Level of perishability	Food loss and wastes %	Country	Source
Guava	High	42.9	Ethiopia	Tadesse (1991)
Tomato	High	19.4		
Carrot	Low	1.1		
Tomato	High	30	Brazil	Vilela et al. (2003)
Carrot	Low	12		

Source: Tadesse (1991) and Vilela et al. (2003)

macronutrients, vitamins, and other nutrients, often resulting in reduced quality or quantity of the foods. These processes are highly dependent on the conditions of the food products, such as temperature, humidity, or insulation. Controlling these parameters is the first step to improving shelf life. Some natural or synthetic chemical compounds can also slow or accelerate the natural degradation (CO_2, ethylene, etc.) of fruits and vegetables or contribute to microbial control/inhibition. Finally, mechanical damages during harvest and post-harvest handling, transportation, or storage can lead to faster metabolic degradation or contaminations (Ndunguru et al. 2000; Ray and Ravi 2005).

Physical damage is a leading cause of post-harvest losses, and the extent of losses is often determined by the commodity's relative susceptibility to physical damage (Kitinoja and Kadar 2015), with more delicate and perishable produce suffering higher losses than less perishable produce (Kitinoja and Kadar 2015) (Table 1.4).

The range of reported losses for diverse crops is extensive (0–80%), which is most likely linked to the perishability of the yield. However, various factors contribute to the high level of food losses, including initial illness incidence in the field, time from harvest, the temperature during handling, weather conditions, kind of packaging used, and so on (FAO 2019).

4.2 Main Drivers Behind Food Losses in Fruits and Vegetables Supply Chains

Food loss and wastes in vegetables and fruits have several roots, resulting from technical or organizational lacks and failure often combined with unfavorable external conditions.

- **Pre-harvest and harvesting practices**: Rough handling during harvest, harvesting at an early or late stage of maturity, lack of proper harvesting material, lack of shade or dedicated space to store harvested fruits and vegetables, and inadequate sorting and grading practices can lead to loss at production and later stages of the supply chain.
- **Inadequate transportation systems**: These result in mechanical, physiological, and microbial damage, which may lower fresh produce quality or promote their

Fig. 1.3 Inappropriate and overcharged packaging of eggplants in bags (**a**) and tomatoes in cardboards (**a**, **b**) (Picture: Victoria Bancal)

rejection. The other reasons are poor roads, breakdowns, lack of proper vehicles, delay in the time between harvest and distribution, and more prolonged produce exposure to bad weather conditions. Moreover, transported in open, unrefrigerated trucks, and other food and nonfood products, it suffers a mechanical injury (compression, abrasion) and rough handling, making them highly vulnerable to qualitative losses.

– **Inadequate or defective packaging**: In low-income developing countries, fruits and vegetables tend to be either poorly packed (Fig. 1.3a, b): wooden crates, overload cardboard, reused plastic bags; or not packed at all. Improper packaging can damage the product, leading to FLW. Furthermore, some fresh products packaged together may cause FLW (e.g.,, a bulk bag of rotten fruits may go unsold) (Dari et al. 2018). However, where crates are used during transit, both quantitative and qualitative losses (product rejected) are significantly reduced (damaged but still saleable).
– **Poor handling and operational performance**: These factors cause mechanical and microbial decomposition of fresh items; rough handling by different FSC members, along with an advanced state of maturity, frequently causes mechanical damage and shortens the shelf life of products, accelerating physiological and microbial damage (Sibomana et al. 2016). Inadequate harvesting equipment and complex handling during harvesting cause bruising and increase the chances of the product coming into contact with the soil, resulting in microorganism contamination.
– **Lack of processing capacity**: It leads to fruits and vegetables being sold primarily in fresh form with a short shelf life. This is primarily the case in developing countries, where modern equipment are lacking, and processing is mainly done on a traditional small scale.
– **Lack of coordination and information sharing among stakeholders of the FSC**: It is also a contributing factor in FLW. According to Mena et al. (2014), the lower the levels of FLW in FSCs, the closer the ties between retailers and suppliers. Lack of information systems on price or production prediction results

in seasonal overproduction at market saturation in developing countries. At the same time, a wrong estimation of the demand may affect food losses at retail markets in developed countries.

- **Poor storage and temperature management**: Fresh products are prone to suffer physiological flaws such as dehydration, freezing, chilling, sunburn, sunscald, and internal breakdown when stored at the incorrect temperature at any stage of the FSC, whether due to a shortage of cold storage and storage facilities or a gap in the cold chain (Dubey et al. 2013). According to Parfitt et al. (2010), 30% of India's fresh fruit and vegetable production is squandered due to a lack of adequate storage facilities. On the other hand, losses in fruits and vegetables in Tanzanian markets were mainly attributed to inadequate cool chain management. But storage facilities also protect food from rodents and insects attack (Ohiokpehai et al. 2009).
- **Climate change and weather variability**: Crop losses in the field can be caused by climate change and weather fluctuation. Crops may suffer obvious damage due to extreme weather events, leading to their rejection. In their contracts with retailers, farmers frequently produce more than specified to account for unpredictable weather situations, resulting in unnecessary overproduction and waste. Where storage facilities are not available, products are expected to be more exposed to rainfall and high temperatures.
- **Sensorial or microbial deterioration**: The natural deterioration of fresh food's physiological, biochemical, and microbiological qualities is linked to sensory or microbial decline. This deterioration is accelerated by factors such as temperature and humidity, which can develop visible defects and rejection (Buzby et al. 2014). Furthermore, diseases and insect pests can significantly impact the pace of microbiological deterioration of fresh products (Fig. 1.4).
- **Short shelf life or expired products**: Fresh products are rejected due to expiration of best-before or sell-by dates or actions taken in collaboration with the FSC that jeopardize the products' shelf life. Fresh products might also go unsold because consumers prefer products with longer expiration dates, believing that a product nearing its expiration date is no longer fresh (Mena et al. 2014).
- **Nonconformance to standards**: Product exclusion can be facilitated by improper weight, unsuitable sizes, forms, or textures of fresh food, as well as evident mechanical or microbiological faults, even if the products are still fit for human consumption. In addition, the presence or absence of appropriate legal criteria can influence whether or not a vegetable or fruit is eventually accepted for human consumption. However, legal standards differ from country to country and are impacted by the population's economic condition and pressure on fruit and vegetable consumption (Sibomana et al. 2016).
- **Overproduction, excessive stocks, and inadequate demand forecasting**: Overproduction might occur due to inaccurate demand forecasting or as a result of agreements with merchants. Combining the characteristic short shelf lives of fresh products with demand fluctuations makes ordering difficult and often leads to overproduction.

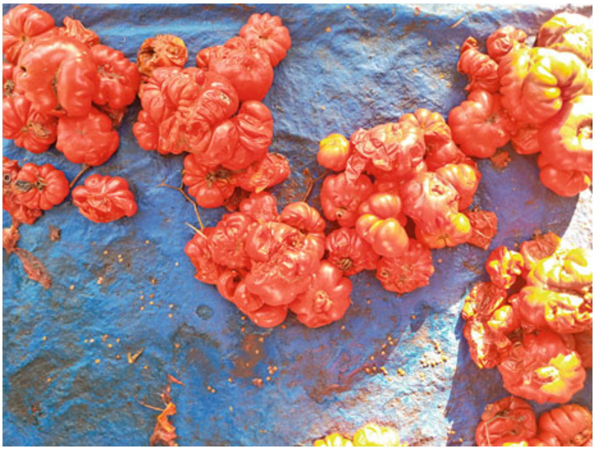

Fig. 1.4 Partly rotten tomatoes sold at a lower price in an Abidjanese market (Picture: Victoria Bancal)

The causes of FLW are not mutually exclusive, and there is a paucity of knowledge about which factors are more influential and how they interact. Causes differ at all stages in food systems and between industrialized as in developing countries and nonindustrialized as in underdeveloped countries. Losses at the production stage are the most important for all industrialized regions, largely due to the sizing of post-harvest fruits and vegetables, the criteria of which are imposed by the distributors. Losses do occur during storage in high-income countries. Nonetheless, they are usually caused by technical breakdown, poor temperature or humidity management, or overstocking. On the other hand, poor infrastructure causes more fresh fruit and vegetable loss in low-income nations than in developed countries (FAO 2019).

5 From Issue to Resources

Fruits and vegetables are the crop group with the highest range of food loss and waste. Their nutritional content makes them great contributors to a healthy diet. Finally, their production, distribution, and disposal as waste require inputs and renewable and nonrenewable resources. As a result, reducing FLW in this category of items should be considered as achieving additional goals, such as increased food system efficiency, enhanced food security and nutrition, and improved environmental sustainability. Policymakers prioritize these different dimensions and will orient the most appropriate interventions to reduce FLW (FAO 2019).

On the other hand, fruits and vegetable wastes (FVW) usually have a composition of sugar, starch, proteins, phenolic phytochemicals, and minerals (Table 1.5), and therefore, they should not be treated as "wastes" but rather as raw materials for other industrial processes. The existence in these FVWs of sugar/starch as a source of carbon, protein as a source of nitrogen, nutrients, and moisture provides conditions

Table 1.5 Biochemical compositions of some vegetables and fruit wastes

Fruit/vegetable waste	Biochemical composition (% w/w)								
	Cellulose	Hemi-cellulose	Lignin	Ash	Total solids	Moisture	Total carbon	Total nitrogen	References
Potato peel waste	2.2	–	–	7.7	–	9.89	1.3	0.48–0.8	Singh et al. (2012); Pathak et al. (2017a)
Cauliflower waste	17.32	9.12	5.94	4.32–5.76	–	81–89	34.48	13.8	Khedkar et al. (2017)
Peapod waste	32.08	21.12	21.58	4.8– 5.20	11.0–39.0	73.5–88.5	–	10.58	Nimbalkar et al. (2018)
Onion peels	–	–	–	4.7– 4.8	91.0	82.0–92.6	–	–	Singh et al. (2012)
Tomato wastes	30–32	5–18	–	3.1–5.3	7.0–22.4	85–90	–	2.72–3.52	Singh et al. (2012)
Carrot peels	13–52	12–19	–	3.8–8.9	7.0–11.0	–	–	0.8–1.28	Singh et al. (2012)
Orange peels	9.21%	10.5%	0.84%	3.5%	–	11.86	–	–	Joshi et al. (2012)
Apple pomace	5–10	4–25	15–25	5.8–6.7	–	15–28	–		Comen et al. (2019)
Pineapple peel	35–50	19.7−35	5–10	4.6–5.8	93.6	75–80	40.8	0.99	Khedkar et al. (2017)
Banana peel	12.17	10.19	16.0	5.01	–	9.65	40.24	1.38	Pathak et al. (2017a, b)
Mango peel	9.2	14.5	4.25	–	–	–	–	–	Gowman et al. (2019)
Papaya peels	–	–	–	3.15–5.25	31–45	54–68	38.10	1.49	Joshi et al. (2012)
Pomegranate peels	–	–	–	–	–	–	–	–	Pathak et al. (2017b)

ideal for the growth of microorganisms, and this opens up great opportunities for their valorization in manufacturing chemicals such as enzymes, organic acids, polysaccharides, sugar alcohols, biocomposites, and biofuels, that is, biochar, bioethanol, biogas, biohydrogen, and biobutanol. FVW generated can be a raw material for other industries (biofuels, biochemicals); hence, researchers should focus on "waste to wealth"—creating a circular economy.

6 Conclusion and Future Perspectives

Fruits and vegetables are a part of a well-balanced regular diet. However, a substantial amount of these commodities is lost from harvesting, handling storage, and marketing during the supply chain. It was not until the 1990s the post-harvest losses of fruits, vegetables, roots and tubers, and plantation crops were given sufficient attention. International attention on the issue is now firmly reflected in the Agenda 2030 for SDG to reduce post-harvest losses of all food crops and valorize wastes into various bioproducts for human and animal consumption as dietary supplements and other valuable products. However, the literature review on the magnitude of losses in fruit and vegetables showed an extensive range of losses from the same crop. For example, the Tanzanian sweet potato value chain suffered a range of 0–33% quantitative losses and 5–80% qualitative losses; in Nigeria, tomato losses were estimated between 10% and 40% from farm to retail (Kitinoja et al. 2019) while under 10% in Nepal (Udas et al. 2005). In front of this complexity, any solution designed to prevent, recycle, or dispose of fruits and vegetables FLW should be context-related and not expected to be generalized to all categories of fruits and vegetables or regions. In addition, information gaps on several crops and regions have to be filled to monitor progress. Finally, the balance between cost and benefits (social, economic, and environmental) of implanting solutions for preventing FLW should be considered while designing these solutions. Therefore, prevention may not always be the most sustainable path to building sustainable food systems. Therefore, research on valorizing the internal properties of surplus or discarded and deteriorated fruits and vegetables should not be neglected.

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Part II
Bioactive Compounds and Extraction Methods

Chapter 2
Recovery of Wasted Vegetables and Fruits for Food Additives

Eva Dorta and Gloria Lobo

Abstract Fruit and vegetable wastes (FVWs) have grown due to their consumption in recent decades. The population is more interested in changing their eating habits and improving their quality of life. In this sense, the consumption of these products allows us to incorporate nutrients and bioactive compounds with health benefits into our diet. Consequently, significant losses and waste in the fresh produce and processing industries are becoming a serious nutritional, economic, and environmental problem. In 2015, the European Union adopted the Sustainable Development Goals found in the 2030 Agenda for Sustainable Development and other actions, all of them to minimize waste. These FVWs are composed mainly of seed, peel, and pomace and are a good source of potentially valuable bioactive compounds, such as carotenoids, polyphenols, dietary fibers, vitamins, and enzymes. These compounds can be utilized in different industries, including the food industry as food additives. This chapter includes a general discussion related to the significance of the reuse of FVWs and their impact on the circular economy and the opportunity of the food industry to transform wastes into food additives with high-value products using different strategies.

Keywords By-products · Wastes · Circular economy · Processing · Anti-nutritional compounds · Bioactive compounds · Functional ingredients

1 Introduction

The Food and Agriculture Organization of the United Nations (FAO) estimates that approximately one-third of the food produced worldwide is wasted. Statistical analysis suggests that, in food systems, fruits and vegetables comprise the most significant portion of food loss and waste (FAO 2011). According to Food Use for Social Innovation by Optimizing Waste Prevention Strategies (EU FUSIONS), food

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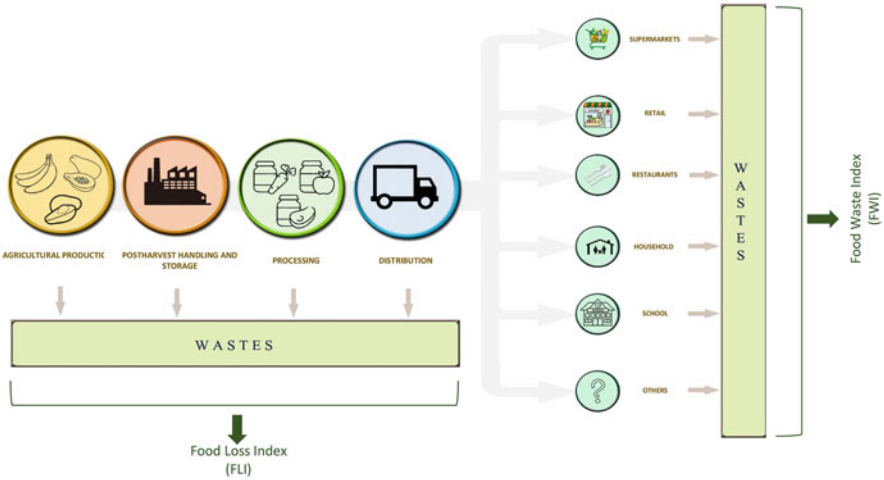

Fig. 2.1 Segments distinguished in the food supply chains of vegetables and the loss index associated with each segment

waste is defined as *"any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed of (including composted, crops plowed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)*" (Stenmarck et al. 2016). FUSIONS was a project aimed at making Europe's food system more resource-efficient by drastically reducing food waste. From August 2012 to July 2016, the project lasted four years. The European Commission Framework Program 7 provided the funding.

The decomposition of wastes in landfills emits harmful greenhouse gases (GHGs), strongly contributing to environmental pollution and related problems. In consequence, decreasing of loss and waste of fruits and vegetables will have a direct benefit for sustainable production and consumption, which is Goal 12.3 of the Sustainable Development Goals (SDGs) adopted in 2015 by 193 Member States of the United Nations portion of food loss and waste (FAO 2011). According to a study carried out for the Swedish Institute for Food and Biotechnology mandated by FAO for International Congress Save Food at Interpack 2011 (FAO 2011), four segments were distinguished in the food supply chains of vegetables, fruits, and animal commodities. Food loss/waste was estimated for each of these segments (Fig. 2.1); only vegetables and fruit wastes were considered below:

- ***Agricultural production***: Losses resulting from mechanical damage and/or spillage during harvest operations (e.g., threshing or fruit picking), post-harvest crop sorting, etc.
- ***Post-harvest handling and storage***: Spillage and degradation losses during handling, storage, and transportation between farm and distribution.

- ***Processing***: Losses due to spillage and degradation during industrial or domestic processing, such as juice production, canning, and bread baking. Losses can occur when crops are sorted out if they are unsuitable for processing, during the washing, peeling, slicing, and boiling processes and during process interruptions and accidental spillage.
- ***Distribution***: This includes market losses and waste at wholesale markets, supermarkets, retailers, and wet markets.
- ***Consumption:*** Losses and waste during consumption at the domestic level are included.

Spiker et al. (2017) presented the amount of nutrients lost due to wasted food in the United States. In particular, results showed (Fig. 2.2a, b) the percentage values of the loss for each nutrient and their food group to which their loss can be attributed. The loss of nutrients such as vitamins, dietary fiber, and most minerals is mainly associated with FVWs. For example, in the case of vitamins, between 16 and 99% of loss comes from FVWs (Fig. 2.1b). A similar situation is observed for dietary fiber (56%), and minerals (12–45%) of their loss are associated with FVWs (Fig. 2.1a). Thus, wastes from fruit and vegetables constitute the main waste with high content of bioactive compounds. In this respect, multiple studies have established that FVWs, which contain proteins, lipids, natural colorants, enzymes, antimicrobials, and antioxidants in addition to the nutrients described above, are a source of natural food ingredients, additives, or supplements with excellent nutritional value (Khattak and Rahman 2017; Lobo and Dorta 2019).

Figure 2.3 is a scheme of the FVWs and the processes for their stabilization and conversion into food additives. To use food additives derived from FVWs, it is important to characterize the type of waste and the destination we want to give it to. Following this, the best strategy for its management can be decided. According to Fig. 2.3, the first stage in which waste is lost is the crop field. It is possible to differentiate between edible and nonedible plant parts, abandoned crops due to damage, low quality, oversupply, pruning waste, and harvest inefficiency. In addition, products can be damaged during transport to the packing houses or the food processing industries, increasing the rejections.

Moreover, waste of peels, seeds, pomace, and offcuts are generated in the food industries, such as those producing wine or oil originate liquid and solid wastes. Therefore, depending on the types of wastes available, different strategies are required for their possible reuse. In any case, one of the main objectives of reuse is to obtain ingredients or food additives that can overvalue existing ones (Augustin et al. 2020). Standard industrial processes, such as drying and extrusion, transform fruit and vegetable wastes into powders, flakes, granules, and pellets (Fig. 2.3) with healthy ingredients. Thus, they can be part of functional foods, beverages, or dietary supplements.

In this chapter, we focus on the use of FVWs to recover them as food additives. The chapter includes a comprehensive discussion related to the importance of the reuse of FVWs and their contribution to the circular economy (CE) and the

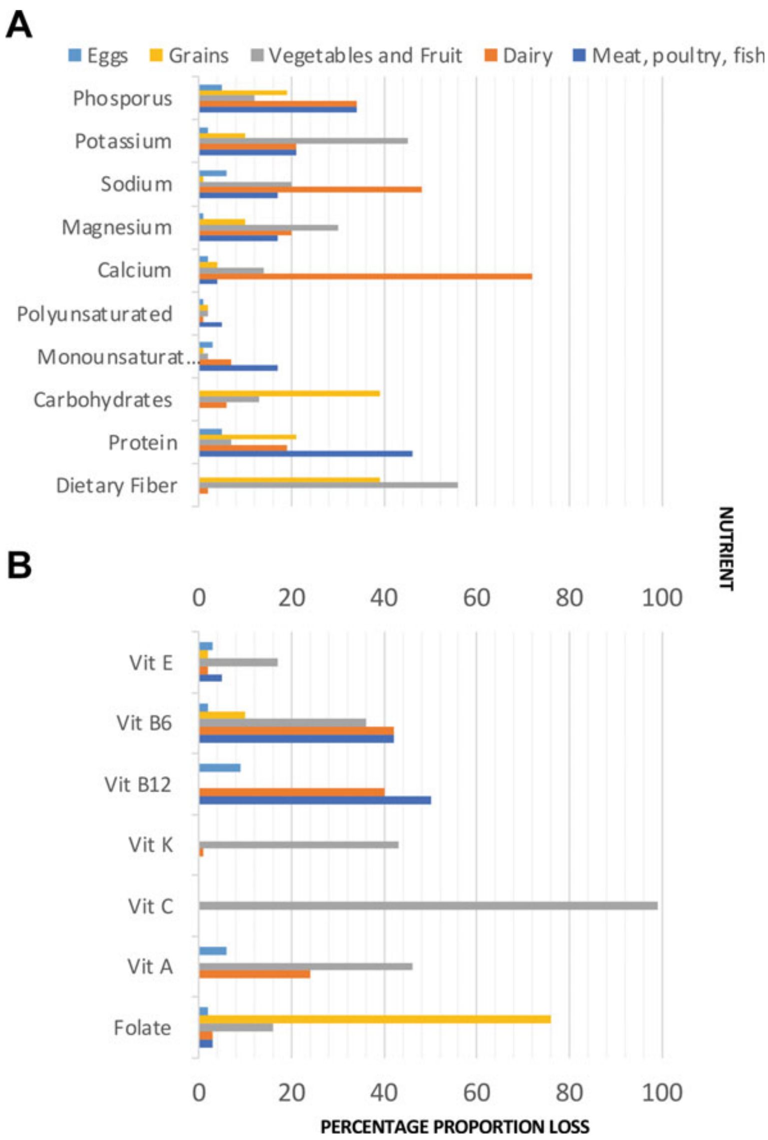

Fig. 2.2 (**a**) Percentage values of the loss for each nutrient (macronutrient and minerals) and their food group to which their loss can be attributed. (**b**) Percentage values of the loss for vitamins and folate and their food group to which their loss can be attributed. (Adapted from Spiker et al. 2017)

opportunity of the food industry to transform wastes into food additives with high-value products using different strategies.

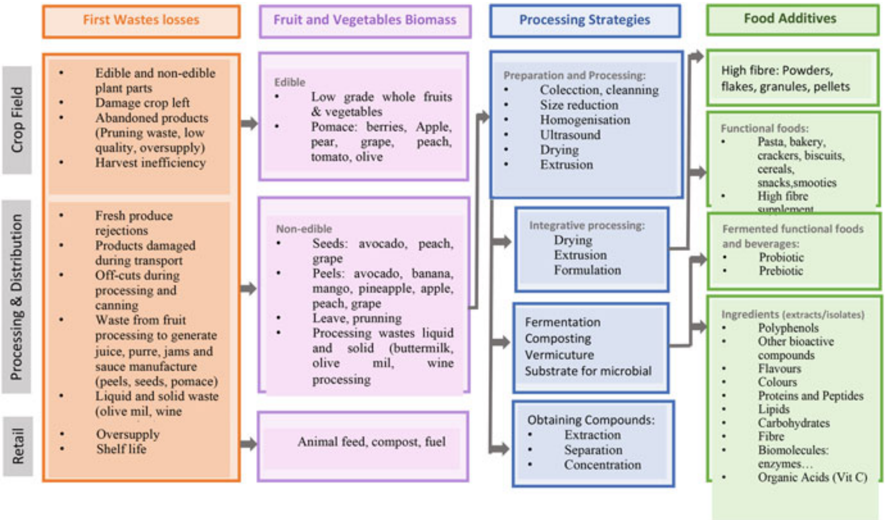

Fig. 2.3 Scheme of the sources of waste fruits and vegetables and processes for the stabilization and conversion of these residues into food additives. (Adapted from Lobo and Dorta 2019; Augustin et al. 2020)

2 Importance of Reuse FVWs

According to the data of the FUSIONS project, around 88 million tons of food waste are generated annually (Stenmarck et al. 2016). In this context, these wastes suppose economic losses (approximately 143 billion Euros) and environmental impacts due to GHG emissions (Torres-León et al. 2018). Therefore, in 2011, the Global Warming Potential of current food waste for the EU was estimated to be around 227 MT of CO_2 equivalents.

In 2015, all the United Nations Member States adopted 17 SDGs at the global level as a fundamental part of the 2030 Agenda for Sustainable Development (United Nations 2015), being an urgent call for action by all countries. Eight SDGs are related directly or indirectly with the importance of reusing plant and fruit waste and are the following (Fig. 2.1):

- SDG 1: End poverty in all its forms everywhere
- SDG 2: End hunger, achieve food security and improve nutrition, and promote sustainable agriculture
- SDG 3: Ensure healthy lives and promote well-being for all at all ages
- SDG 6: Ensure availability and sustainable management of water and sanitation for all
- SDG 8: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
- SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation

- SDG 12: Ensure sustainable consumption and production patterns
- SDG 13: Take urgent action to combat climate change and its impacts

On the other hand, FAO and United Nations Environment Program (UNEP) have developed two indicators to track progress toward the SDG on food loss and waste (SDG 12.3):

- ***The Food Loss Index*** (**FLI**, Indicator 12.3.1a) measures losses for key commodities in a country across the supply chain, up to and not including retail. The FAO is its custodian.
- ***The Food Waste Index*** (**FWI**, Indicator 12.3.1b) measures food and inedible parts wasted at the retail and consumer levels (household and food service). The United Nations Environment Program (UNEP*)* is its custodian.

Unlike the FLI, the FWI evaluates overall global food waste (rather than individual commodities) and estimates that 931 million tons of food were wasted in 2019, with 61% coming from households, 26% from food service, and 13% from food service from retail (Fig. 2.1). Similarly, in the EU, homes account for more than half of all food waste (47 million tons), with 70% of food waste generated in the house, food service, and retail sectors (Stenmarck et al. 2016; Hamish et al. 2021).

According to the FAO, 690 million people were hungry in 2019, and this number is anticipated to rise during and after COVID-19. Furthermore, research from 2020 showed that nearly 3 billion individuals could not afford a healthy diet (FAO 2020). On the other hand, the continuous growth of the world population implies an increase in food consumption that results in pressure on the environment due to the generation of food and the amount of waste resulting.

The recommendations of FAO to achieve the object of SDG 12.3 target by 2030 involves accelerating progress and halving global food waste, especially food losses along production and supply chains, including post-harvest losses (Hamish et al. 2021) (Fig. 2.1). It is important to note that the FLI estimates that around 14% of the world's food is lost after harvest, but excluding the retail level (FAO 2019).

Fruit and vegetables have antioxidative, anticarcinogenic, antiatherosclerotic, antimutagenic, and angiogenesis inhibitory qualities, contributing to human health benefits (Dorta et al. 2014). Consequently, their production, trade, and consumption have increased significantly, leading to an increment of waste of these products (Campos et al. 2020; Garcia-Herrero et al. 2019).

Regarding fruits and vegetables, a brief resume of these wastes is presented in Table 2.1. In general, fruit and vegetable waste is a good source of bioactive compounds such as vitamins, dietary fiber, proteins, fats, natural colorants, enzymes, antimicrobials, and antioxidants (Khattak and Rahman 2017; Comunian et al. 2021). Therefore, the main reasons for reusing fruit and vegetable waste are:

- Diminution of the environmental impact is mainly due to reducing the amount of waste in landfills and, therefore, decreasing GHG emissions.
- Recovery of the bioactive compounds present in them.
- We obtain natural food ingredients, additives, or healthy supplements from low-cost raw.

Table 2.1 Main bioactive compounds identified in different fruit and vegetables wastes

Fruit/ vegetable	Biowaste	Bioactive compounds	References
Pineapple	Peel, leaves	Phenolic compounds	Dorta and Sogi (2017), Silva et al. (2020) and Yadav et al. (2021)
Avocado	Peel, seed, leaves	Phenolic compounds, Carotenoids, Tocopherols, Sterols	Jimenez et al. (2021)
Banana	Peel	Phenolic compounds, Dopamine, L-dopa, campesterol and stigmasterol	Silva et al. (2020) and Yadav et al. (2021)
Mango	Peel, kernel	Phenolic compounds, carotenoids, anthocyanins, ascorbic acid	Jahurul et al. (2015), Mwaurah et al (2020) and Yadav et al. (2021)
Citrus	Peel	Phenolic compounds	Yadav et al. (2021)
Pomegranate	Peel, mesocarp	Phenolic compounds	Yadav et al. (2021)
Watermelon	Rind, seed	Phenolic compounds, antinutrients, ascorbic acid and others vitamins	Zia et al. (2021)
Papaya	Peel, seed	Phenolic compounds, carotenoids, anthocyanins, ascorbic acid	de Moraes Crizel et al. (2016) and Silva et al. (2020)
Grape	Pomace	Phenolic compounds	
Tomato	Peel, core, seed	Phenlic compounds, carotenoids, nucleosides	Viuda-Martos et al. (2014) and Palomo et al. (2019)
Potato	Peel	Phenolic compounds	Akyol et al. (2016)
Olive	Tree cultivation, oil industry	Phenolic compounds, polyols, fatty acids	Gullón et al. (2018, Gullón et al. 2020)
Wheat	Milled wheat	Phenolic compounds, dietary fiber, tocopherol, tocotrienols	Smuda et al. (2018)
Rice	Husk, bran, milled rice	Phenolic compounds, dietary fiber, tocopherol, tocotrienols	Moh Esa et al. (2013) and Smuda et al. (2018)

- Development of various bioproducts where nontoxic organic solvents and low energy consumption help solve global problems and achieve the circular economy's objectives.

3 The Concept of Circular Economy

In today's academic, industrial, and political worlds, concepts like circular economy, sustainability, and renewable energy are commonly used (Cuadros Blázquez et al. 2018). For example, the circular economy (CE) is a paradigm that advocates for more responsible and appropriate resource exploitation and utilization of resource-rich by-products, as opposed to the linear "take-make-dispose" approach (Santagata et al. 2021).

3.1 Evolution of the Concept of Circular Economy

To understand the circular economy concept, it is necessary to know the classic model of production so-called linear system of production (lineal economy), based on a scheme consisting of extraction and/or obtaining, use, consumption, and final disposal of the product (Cerantola and Ortiz Pinilla 2018). Therefore, the lineal economy is a disposable model that exploits natural resources to transform them into products, consume them, and generate waste. Using fossil fuels, it has begun to teach its limited product (Cerantola and Ortiz Pinilla 2018). In addition, social, economic, and environmental problems have been generated due to this model. In 2015, European Parliaments defined a circular economy "*as a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible to create added value*" (European Parliament News 2015). Therefore, as opposed to the lineal economy, the circular economy promotes a new model whose purpose is to decouple global economic development from the consumption of finite resource products (Cerantola and Ortiz Pinilla 2018).

Recently, the Covid-19 health crisis affected both health and the world economy. So the European Commission presented, in May 2020, a recovery plan under the name of European Green Deal with a line of action based on proposing a new strategy for the circular economy, in which proposals on more sustainable product design, reducing waste, and empowering consumers (such as a right to repair) are included (European Parliament News 2020).

3.2 Objectives of Circular Economy

In general, the objective of circular economy is intended to extend the life cycle of the products, as shown in Fig. 2.4. The circle of the circular economy starts with raw materials, which are subjected to processes of design, production, or remanufacturing depending on the origin of that product (wastes or initial raw material from crop field). In addition, due to the distribution of products, residues are also generated, which in the case of vegetables and fruits, suffer damage during transport or due to a wrong post-harvest. Therefore, these wastes must be incorporated into the circular economy (European Parliament News 2015) by reusing them as a source of bioactive compounds.

Additional steps, such as stricter recycling standards and enforceable targets for materials, usage, and consumption by 2030, are demanded in the new circular economy action plan to achieve a carbon-neutral, environmentally sustainable,

Fig. 2.4 Scheme from Circular Economy© @ European Union

toxic-free, and fully circular economy by 2050. Furthermore, these goals are aimed at making Europe a greener, more inclusive, digital, and sustainable place, as well as increasing resilience to future crises by focusing on waste prevention and management, as well as enhancing growth, competitiveness, and EU worldwide leadership (European Parliament News 2021; Campos et al. 2020).

3.3 Advantages of Implementation of Circular Economy

In this context, the recovery of wasted vegetables and fruits for food additives represents a significant challenge for both the food industry and governments, in such a way that if procedures for their reuse are carried out, the European challenges could be met in 2050.

Among the benefits that can be highlighted to the implementation of the circular economy (European Parliament News 2015) are:

REDUCTION in total annual greenhouse gas emissions
REDUCTION of pressure on the environment
IMPROVE the security of the supply of raw materials
STIMULATE competitiveness, innovation, economic growth, and employment

PROVIDE consumers with more durable and innovative products that provide monetary savings and a higher quality of life

SAVING money for EU companies employing waste prevention, eco-design, and reuse measures

In the agri-food industry, the reintroduction of FVWs in the production line as a raw material rich in bioactive compounds entails advantage for both industry and society due to products with high added value can be obtained from waste. Furthermore, this would mean economic and environmental benefits that would allow meeting the main objectives on which the circular economy is based (Del Rio Osorio et al. 2021) (see Sect. 2). As a result, the circular economy appears to be a viable option for preventing, reusing, or recovering natural resources and by-products derived from industry in the medium and long term.

4 Challenges and Opportunities for the Reuse of FVWs

The reuse of FVWs represents meaningful opportunities from an economic, environmental, and social point of view. Recently, a study related to food wastes, their challenges, and opportunities shows the possibilities in the area based on an exhaustive analysis of the works carried out so far on this topic (Santagata et al. 2021).

As presented in Sect. 1 (Fig. 2.3), there are different strategies to reuse waste depending on the type of pretreatment and/or according to the conversion process (Lobo and Dorta 2019; Santagata et al. 2021). In Table 2.2, some examples are shown for each type of strategy. In addition, different products are obtained from FVWs depending on the process carried out (Table 2.2). Among the products obtained through FWS that suppose an important opportunities are biofuels (e.g., bioethanol, biogas), bio-fertilizer (e.g., biochar), starch, pectin, cellulose, obtaining natural colorants, dietary nutrients and fiber bioactive compounds.

Table 2.2 Different strategies to reuse waste depending of the type of pretreatment and/or according to the type of conversion process

Pretreatment process	Conversion process
Biological: aerobic fermentation[a]	Biological: anaerobic digestion[b]
Chemical: hydrolysis	Chemical: transesterification
Physical: extrusion, homogenization	Physical: UAE or MAE[c]
Physicochemical: UAE[c] with acid, organic solvents	Physicochemical: upgrading,
Thermal: drying, freeze-drying	Thermal: incineration, pyrolysis
Thermochemical: organosolvation	Thermochemical: liquefaction

Adapted by Lobo and Dorta (2019) and Santagata et al. (2021)

[a]Composting

[b]Vermiculture

[c]ultrasound-assisted or microwave-assisted extraction

4.1 Bioethanol

Bioethanol is the most frequently utilized biofuel in the world for transportation. Agricultural products account for almost 95% of all ethanol generated worldwide. Direct fermentation of simple sugars or polysaccharides (e.g., starch or cellulose) that can be converted to sugars produces bioethanol. The fermentation of carbohydrates into ethanol is followed by their separation and purification (Lobo and Dorta 2019).

4.2 Dietary Fibers

Nowadays, the growing interest in gastrointestinal health has searched for compounds, a topic of global interest. Dietary fibers are complex carbohydrates, non-starch polysaccharides (cellulose, dextrins, chitins, pectins, glucans), and lignin, promoting bifidobacteria lactobacilli growth and activity. Therefore, they modulate the transit time through the gut and form bulk in stools (Wichienchot and Wan Ishak 2018). These compounds are found naturally in FVWs. For example, pectic oligosaccharides and fructooligosaccharides are generated from fruit and vegetable processing and the sugarcane industry, xylooligosaccharide from wood and corncob, and ß-glucan from cereal and mushroom by-products, while soybean oligosaccharide is a by-product from the tofu and soy protein industry (Wichienchot and Wan Ishak 2018). Therefore, these compounds are found naturally in FVWs.

4.3 Bioactive Compounds

Peels, seeds, stones, and whole pieces of fruit and vegetables are regarded as sources of phytochemicals and other valuable products (de Ancos et al. 2015). The content of bioactive compounds in different FVWs depends on the evaluated products, as shown in Table 2.1. In general, the peel and seed are the principal FVWs in the fruit and vegetable industry, located mainly in phenolic compounds, vitamin C, and carotenoids (de Ancos et al. 2015; Gowe 2015). Following is a summary of the principal bioactive compounds present in FVWs.

4.3.1 Ascorbic Acid

The best example of its possible usage in the food sector is ascorbic acid, often known as vitamin C, a natural compound derived from numerous plant tissues. Numerous FVWs contain vitamin C and other vitamins, such as vitamins E and

A. Vitamin C (E300) is used principally as an antioxidant additive. Therefore, it can avoid enzymatic browning in fruit (Faustino et al. 2019; Gowe 2015).

Grape is a fruit that has been widely studied due to its numerous health advantages. Torres-León et al. (2018) found that grapes are high in vitamins B6, thiamine (vitamin B1), and vitamin C. Other residues with high amounts of vitamin C are cauliflower by-products, corn by-products, beets by-products, and peel and seed from tropical fruits, among others (de Ancos et al. 2015; Faustino et al. 2019; Gowe 2015; Torres-León et al. 2018).

4.3.2 Carotenoids

Carotenoids are the primary group of compounds used as color additives. Many colors of edible fruits, vegetables, mushrooms, and flowers may be traced back to these natural pigments. They are found in the peel and pulp of mango, papaya, apricot, carrot, orange, and pumpkin (Faustino et al. 2019; Jaswir et al. 2011). In addition, they function as sources of provitamin A and can absorb solar light, oxygen transporters, and potent quenchers of singlet oxygen, among other attributes (Faustino et al. 2019). Carotenoids are primarily found in tomato remnants (skin and seed wastes) specially lycopene, which is the major pigment responsible for the red color (Torres-León et al. 2018). The mango peel also contains a considerable amount of carotenoids among which are all-trans-β-carotene, 9-cis-β-carotene, all-trans-lutein, and 13-cis-β-cryptoxanthin, β-carotene 5,6 epoxide, β-xanthophylls, apocarotenoids, all-trans-zeaxanthin, 9-cis-zeaxanthin, 9-cis-β-cryptoxanthin, and 15-cis-β-cryptoxanthin (de Ancos et al. 2018; del Pilar Sánchez-Camargo et al. 2019).

Natural pigments were defined in the European Parliament and Council Regulation (EC) No 1333/2008 on December 16, 2008. In the case of carotenoids (E160), β-carotene (E160a), lycopene (E160d) (its obtention from tomato processing by-products has been optimized), lutein (E161b), and canthaxanthin (E161g) are included (Faustino et al. 2019).

4.3.3 Phenolic Compounds

Phenolic compounds, as a large group of natural antioxidants present in fruits and vegetables, are molecules whose structure contains one or more benzene rings. In addition, at least two hydroxyl groups are attached (Gowe 2015; Speisky et al. 2016). Traditionally, from a structural point of view, these compounds are divided into flavonoids and non-flavonoid phenolic, which exhibit remarkable antioxidant activity. This classical view emerged from these compounds' well-established in vitro ability to scavenge reactive oxygen species (ROS) (Speisky et al. 2016; Dorta and Sogi 2017).

Several experimental evidence supports the concept that at least a significant part of the benefits of the regular consumption of fruit and vegetables has been associated with their phenolic compound content. Besides, the peels, seeds, and other residues generated from the processing of fruits and vegetables have been found to contain significant amounts of phenolic compounds (Table 2.1). Therefore, they can potentially be applied in the food industry as food additive sources (Faustino et al. 2019). In recent years, some databases have been developed to know the content in phenolic compounds and their antioxidant activity in food, fruits, and vegetables (http://www.portalantioxidantes.com/; http://phenol-explorer.eu/) (Speisky et al. 2016).

Nowadays, some additives are obtained from agri-food by-products. They are allowed under Regulation (EC) No 133/2008. They can be found in agro-food by-products, such as anthocyanins (E163) in grape/winemaking by-products or chlorophylls (E140) in practically all green leafy vegetable by-products or mango peels (Faustino et al. 2019). Tropical fruits are the major source of phenolic compounds, which include mango, pineapple, avocado, papaya, and bananas being the main important crops worldwide; therefore, they are the main generators of residues (Dorta et al. 2014; de Moraes Crizel et al. 2016; Dorta and Sogi 2017; Acevedo et al. 2021; De la Luz Cádiz-Gurrea et al. 2020; Jimenez et al. 2021). The attraction to these fruits stems from their sensory characteristics, exotic nature, and undisputable nutritional values linked to health-promoting activities (De la Luz Cádiz-Gurrea et al. 2020). Dorta et al. (2014) have reported the value of mango by-products as a source of natural bioactive phenolic compounds. They found 30 phenolic compounds in mango peels, and seeds belonged to five phenolic families: gallates and gallotannins; flavonoids, primarily quercetin derivatives; ellagic acid and derivatives; xanthones, primarily mangiferin; and benzophenones and derivatives, including maclurin derivatives.

Polyphenols are the most common bioactive components found in avocado pulp and waste (peel, seed, and leaf), followed by carotenoids, tocopherols, and sterols. Polyphenols can be found in the pulp, peel, seed, and leaves of avocados, whereas carotenoids and tocopherols are mostly found in the pulp. Procyanidins (PCs) are the major polyphenol compounds detected by high-performance liquid chromatography (HPLC) in avocado pulp, seed, peel, and leaf, with their content in seed (2370–5560 mg/100 g) and peel (490–29,080 mg/100 g) being exceptionally high (Jimenez et al. 2021).

Other fruits, such as kiwi, guava, red dragon, longan, and sapodilla, have considerable antioxidant activity and polyphenol content, making them a viable contender for use as food additives to preserve and enhance quality while preventing food oxidation (Gowe 2015).

4.4 Opportunities for the Reuse of FVWs

In general, the opportunities to obtain the products mentioned from low-cost raw materials led to a new paradigm where the concept of waste disappears and is replaced by that of a resource, which is considered a nutrient that can be used by nature, industry, or society (Cerantola and Ortiz Pinilla 2018). In this context, the implementation of the circular economy implies the following opportunities divided into three blocks (Cerantola and Ortiz Pinilla 2018; Santagata et al. 2021):

(i) ***Economic Opportunities***

- *Increase economic growth*
- *Creation of employment opportunities*
- *Savings in raw material cost*
- *Innovation*

(ii) ***Benefits for the Environment***

- *Lower carbon dioxide emissions*
- *Lower consumption of raw materials*
- *Preservation and improvement of productivity and soil health*
- *Reduction of air and water pollution, discharge of toxic substance, and therefore diminution of climate change*

(iii) ***Social Impacts***

- *Increase family income due to lower cost of products and services.*
- *Higher quality and more local employment.*
- *By increasing the durability of products or their reuse, there will be an improvement in the economy and quality of life of people.*

4.5 Eco-innovation and Eco-design

To achieve all the opportunities mentioned above due to the strict application of a circular economy model, it is necessary to be accompanied by changes and/or challenges that lead to innovation in industrial processes, thus incorporating the concepts of eco-innovation and eco-design.

Eco-innovation has been characterized as an innovation that benefits both the environment and the economy (product, process, marketing, organizational). As a result of the development of competitive technologies that allow for environmental benefits, such as better efficiency in consumption and resource usage, eco-innovation has been acknowledged as a critical element in the shift from a linear to a circular system of production and consumption (de Jesus et al. 2016). Furthermore, as a part of eco-innovation, ***eco-design*** is defined as the *systematic integration of environmental aspects into product design to improve its environmental performance throughout its whole life cycle* (den Hollander et al. 2017).

The strategies on which eco-innovation and eco-design are based will allow the manufacturing of products to be conducted from an economic, social, and environmental perspective, starting from their design and taking into account the following premises (Cerantola and Ortiz Pinilla 2018):

- The choice of raw materials with less impact
- The use of the best technologies in production processes
- Improving its functions
- The satisfaction of consumers
- The reduction of the environmental impact in use
- The lowest consumption of resources in manufacturing and use
- The reduction of the environmental impact at the end of the useful life of the products

The proposed changes and/or challenges lead to the so-called Industry 4.0. This fourth industrial revolution is based on the concept of smart factory where there is an entirely new approach to production (Crnjac et al. 2017). The main characteristic is the interconnection of processes, products, and services through the massive and intensive use of mobile internet, artificial intelligence, and sensors, optimizing efficiency globally (Cerantola and Ortiz Pinilla 2018).

The goal also encompasses the management of nutritional problems through the valorization of food wastes, as this could be envisaged to minimize malnutrition, hunger, and the accompanying ill environmental impacts of food wastes.

5 Anti-nutritional Compounds

Compounds or substances that interfere with nutrient absorption and limit nutrient intake, digestion, and utilization are anti-nutritional substances (Popova and Mihaylova 2019). The effect of these compounds on the reutilization of FVWs will be examined in this section.

5.1 Definition and Classification of ANCs

The anti-nutritional compounds (ANCs) are substances generated by the normal metabolism of natural foods with contrary effects to optimum nutrition. Most ANCs are found in several plants' seeds or other parts (Thangaraj 2016). Phytate, phenolic compounds, lectin, enzyme inhibitors, saponins, oxalic acid and oxalates, and fiber are the principal ANCs (Fig. 2.5). Their presence in plant foods limits bioaccessibility and bioavailability of minerals and other nutrients (Nikmaram et al. 2017; Raes et al. 2014). The secondary metabolism of plants generates the ANCs as a defense mechanism to stressful situations or against mold attack, bacteria, insects, or birds. ANCs are classified as:

- *Thermostable factors* include antigenic factors, oligosaccharides, toxic nonprotein amino acids, saponins, estrogens, cyanogens, and phytates (Elizalde et al. 2009).

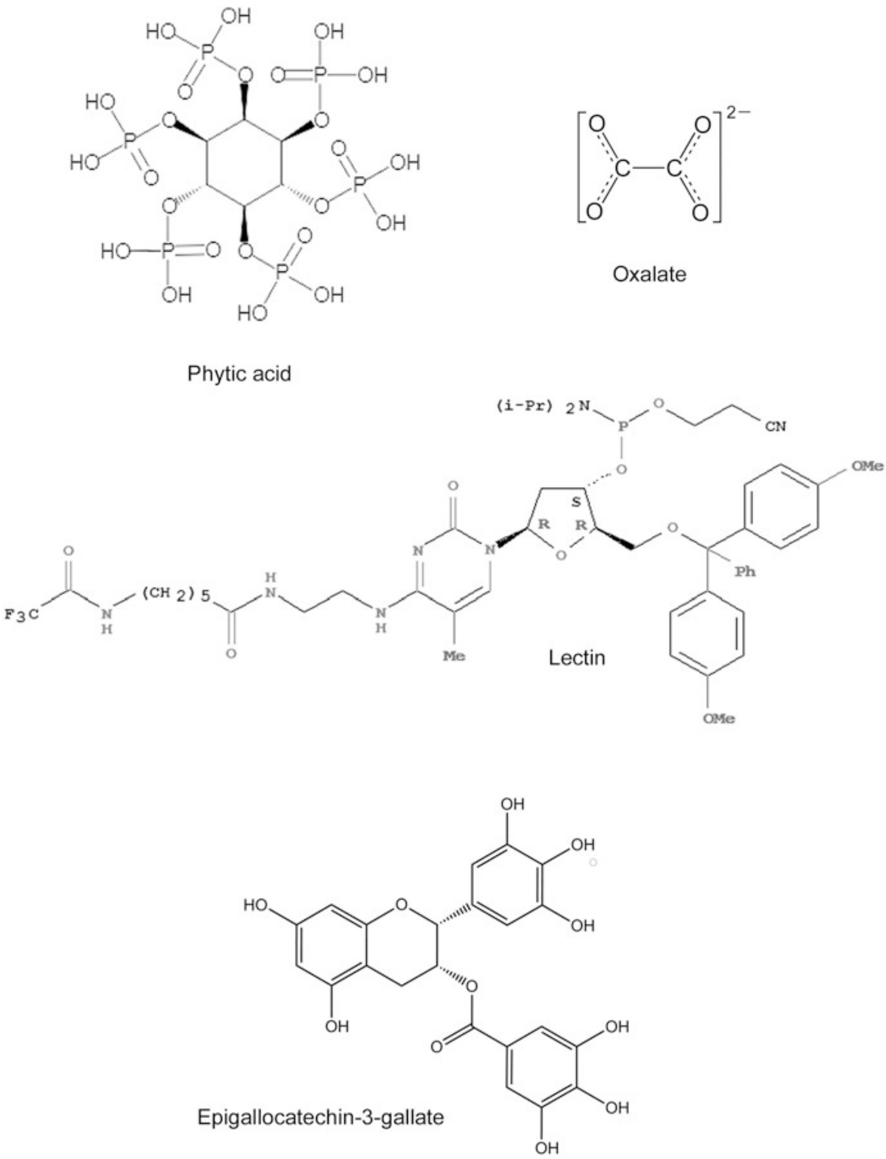

Fig. 2.5 Chemical structure of selected anti-nutritional compounds in food

- *Thermolabile factors* include protease inhibitors (trypsin and chymotrypsin), lectins, goitrogens, and antivitamins (Elizalde et al. 2009).

The consumption of plant foods (grains, beans, legumes, nuts, leaves, roots, and fruits) with significant amounts of ANCs commonly generates symptoms such as nausea, bloating, headaches, rashes, and nutritional deficiencies (Popova and

Mihaylova 2019). Nonetheless, numerous studies have revealed that the intake of low amounts (low doses) of ANCs could be beneficial for preventing several diseases (Olaseni et al. 2020). Low amounts of phytic acid, lectins, phenolic compounds, enzyme inhibitors, and saponins, for example, have been demonstrated to lower blood glucose, plasma cholesterol, and triacylglycerol levels. Furthermore, additional research has shown phenolic substances, phytic acid, protease inhibitors, saponins, lignans, and phytoestrogens to lessen cancer risks. On the other hand, the tannins were discovered to have antiviral, antibacterial, and antiparasitic properties (Olaseni et al. 2020). Thus, it is accepted that although they lack nutritional value, they would not be harmful in small quantities, just the contrary. For such reason, the term "non-nutritive compounds" or "factors nutritionally bioactive" is preferred instead of anti-nutritional compounds. This has led to considering all those foods containing non-nutritive compounds as functional foods (Elizalde et al. 2009).

5.2 Processing Technologies to Remove ANCs

As mentioned in the previous sections (Sects. 2 and 4), wasted vegetables and fruits are a good source of nutrients such as proteins, carbohydrates, minerals, vitamins, dietary fibers, and bioactive compounds. Several works have explored and identified ANCs in wasted vegetables and fruits. These compounds can bind to nutrients and thus reduce their absorption in the gastrointestinal tract, implying a lower nutritional value of these wastes (Nikmaram et al. 2017). Nevertheless, different processing technologies, like mechanical treatments, soaking, cooking, germination, radiation, fermentation, heating, and chemical treatment, remove undesirable food components such as ANCs and enhance their quality, and therefore, the bioaccessibility of the nutrients increases and decreases the effect of anti-nutritional compounds (Olaseni et al. 2020; Popova and Mihaylova 2019; Raes et al. 2014).

- *Cooking*. Heating during cooking mainly at temperatures below the boiling point for 15 min favors decreasing anti-nutritional compounds such as phytic acid, oxalic acid, protease inhibitors, and tannins. The cooking time required is generally influenced by the type of ANCs, food plants, and the cooking method employed (Olaseni et al. 2020).
- *Fermentation*. Different works reported the reduction of phytic acid, polyphenol, hydrogen cyanide, oxalate, protease inhibitor, and tannin in foods such as soybean, cowpea, and sorghum using fermentation (Olaseni et al. 2020).
- *Germination*. Also known as sprouting, it is one of the most effective processes for reducing ANCs. During germination, there is an increase in the availability of nutrients in grains, legumes, and seeds and a decrease in ANCs (Olaseni et al. 2020; Popova and Mihaylova 2019).
- *Soaking*. This procedure is traditionally used in legumes, where soaking them overnight reduces ANCs to an unperceivable level. It also reduces ANCs such as tannins phytate, calcium oxalate, protease inhibitors, and lectins in nuts, seeds,

and leafy vegetables. In general, soaking is effective because ANCs are found on the skin and tend to dissolve easily when immersed in water because they are soluble in it (Olaseni et al. 2020; Popova and Mihaylova 2019).

- *Radiation.* Gamma radiation has been widely used to decrease ANCs such as trypsin inhibitors, phytic acid, and oligosaccharides. However, no significant changes in the tannin content have been observed (Olaseni et al. 2020).

Despite each of the methods discussed could be highly effective in reducing the level of ANCs in food samples. Combining various ways is more efficient in the total degradation of ANCs (Olaseni et al. 2020).

6 Industrial Applications Developed

The health crisis experienced due to worldwide COVID-19 disease, as mentioned above (Sect. 3), affected the world economy and the food industry, especially production (Del Rio Osorio et al. 2021; Galanakis 2020). In this perspective, both the government and consumers have recognized the importance of focusing on their health, particularly their immune system, by adopting healthier diets and demanding or requiring bioactive substances in food and functional foods. Furthermore, food safety is a primary concern to prevent the virus from spreading among producers, merchants, and consumers (Galanakis 2020). On the other hand, governments insist on environmental maintenance and reducing organic waste to avoid CO_2 in the atmosphere and the corresponding greenhouse effect. However, as already mentioned, all wastes are generally released in landfills or burned for energy production, which in addition to an environmental problem leads to loss of the economic and biological value of these by-products (Campos et al. 2020).

Food additives (antioxidants, antimicrobials, colorants, flavorings, and thickening agents) are one of the principal uses for FVWs in the food business (Gowe 2015). In this sense, the opportunity to extract value-added compounds from raw materials of fruit and vegetable wastes supposes a significant economic benefit. This section shows examples of industrial applications related to the use of FVWs.

6.1 Source of Food Additives for Industrial Applications

Several works have been demonstrated the value of FVWs as a source of food additives. The US Food and Drug Administration defines a food additive as “any substance whose intended use results in or may reasonably be expected to result – directly or indirectly – in it becoming a component of or otherwise influencing the properties of any food” (FDA 2010). Food additives are also defined by the European Food Safety Authority (EFSA) as “*substances added purposefully to* *foodstuffs to perform certain technological purposes, such as coloring, sweetening, or preserving foods*" (EFSA 2009).

6.1.1 Banana Industry

The banana industry generates a lot of lignocellulosic waste, which can be used in various ways, including biofuels, wastewater treatment, bioplastics, organic fertilizer, and nanotechnology (Acevedo et al. 2021).

Because of its abundance and wide availability, lignocellulosic biomass from banana peels, pseudostems, and rachis has been used as a raw material for ethanol production. Recently, the peel from green leftover bananas was employed as flour in gluten-free cakes, another alternative for the reuse of banana waste (Acevedo et al. 2021; Martin Lorenzo et al. 2021). Alzate-Arbeláez et al. (2019) developed a polyphenol nanocellulose complex using banana rachis that showed antioxidant activity when used in the emulsified system of Sacha inchi (*Plukenetia volubilis*, a perennial plant native to certain parts of South America and the Caribbean) oil exposed to accelerated oxidative conditions (Alzate-Arbeláez et al. 2019). Besides, the nanocomplex inhibits the oxidative modifications of a peptide tryptophan residue. Therefore, this novel powder material can be regarded as a good alternative for the food industry to replace synthetic antioxidant additions (Alzate-Arbeláez et al. 2019). It is made by simply impregnating a polyphenolic-rich natural extract on a porous nanomaterial derived from banana waste.

In orange juice, banana peel extract is employed as an antioxidant source. The findings show that banana peel is a suitable natural ingredient for increasing the capacity of orange juice to scavenge free radicals while maintaining acceptable sensory and physicochemical properties for consumers (Ortiz et al. 2017b). Another work with orange juice and banana peel extract was related to the capacity of the banana peel extract to stabilize orange juice during its pasteurization and cold storage (Ortiz et al. 2017a). In this study, the panelists found it difficult to detect differences between freshly squeezed orange juices and orange juices from concentrate with and without banana peel extract versus conventional juices. Therefore, adding banana peel extract to squeezed orange juices and orange juices from concentrate is an excellent alternative for reusing this waste in the food industry (Ortiz et al. 2017a, 2017b).

6.1.2 Pineapple Industry

Recently, Campos et al. (2020) presented a case study on the circular economy in the pineapple industry, although this example can be applied to different industries, mainly food processing industries. The pineapple processing industry produces large quantities of solid and liquid wastes (Dorta and Sogi 2017). According to Campos et al. (2020), three groups of residues can be identified in pineapple processing: G1 (crowns, peels, core, trimmings, rotten and too ripe fruit), G2 (crowns, peels, pomace, rotten fruit, solid cake), and G3 (crowns, press cake). G1 corresponds with waste from the pineapple low processed fruit industry, G2 relates to high process fruit, and G3 with enzyme production (Campos et al. 2020). From industry G3, the waste could be utilized to produce biofuels such as bioethanol or biogas (Campos et al. 2020; Dorta and Sogi 2017). While from industry, G1 and G2 waste could be used to generate functional food or/and in different applications in the pharmacological industry. Besides, green chemistry processes can be used to obtain enzyme (bromelain), prebiotics products, and other nutraceuticals or bioactive compounds from liquid waste (Campos et al. 2020; Dorta and Sogi 2017).

6.1.3 Olive Oil Industry

The industry of olive oil generates important economic and health benefits; however, their waste creates an environmental problem. Nevertheless, these wastes still contain high-added value compounds, so their extraction would convert them into excellent low-cost sources of bioactives such as antioxidants, carbohydrates, fiber, and pigments, among others (Gullón et al. 2020). In this sense, significant efforts have been made in the last years to obtain these high-quality phytochemicals while preserving their functional properties through green technologies combined with environmentally friendly solvents (Gullón et al. 2020). The principal added-value compounds obtained from the proposed olive oil waste have been polyols and fatty acids. The applications of these compounds in the food industry are related to their preserving characteristic due to phenolic compounds obtained from olive leaves. On the other hand, olive leaves have been employed to delay or reduce lipid oxidation and improve its properties and shelf life stability. Moreover, food supplements in the hens' diet result in long-chain omega-3 fatty acids enriched eggs (Gullón et al. 2020).

6.1.4 Juice and Jam Industry

The wastes from fruit and vegetables are a good source of dietary fiber. For example, apple peel and pomace are waste materials from apple juice processing and contain significant amounts of dietary fiber that could be used as food additives (Sagar et al. 2018). Other wastes with an important dietary fiber content are grape pomace, mango peel and seed, and citrus peel (Sagar et al. 2018).

Gómez-López et al. (2021) explored the new potential of the industrial by-products of *Opuntia stricta* var. *Dillenii* (peel, bagasse, whole fruit (nonuniform and noncommercial fruits), an intermediate product (raw juice)) as new resources to obtain biologically active food ingredients. The study focused on the stability and bioaccessibility of betalains and phenolic compounds in the nonedible part of *O. stricta* var. *Dillenii* fruits. The findings revealed that *Dillenii* fruit peel and fresh whole fruit are the most promising sources of antioxidant extracts rich in betalains and phenolic compounds with high bioaccessibility. However, due to its reduced level of betalains and phenolic compounds and its limited bioaccessibility, the by-product from jam manufacturing was not attractive to employ as a starting material to create bioactive extracts (Gómez-López et al. 2021).

6.1.5 Textile Industry

In addition to the food industry and food additive innovation, many textile companies are trying to find new ways to make innovative and environmentally sustainable fabrics. An example of this is Eco-Age (https://eco-age.com/about/), which is specialized in consulting to create a sustainable business strategy (Eco-Age 2021). They have developed six sustainable fabrics with products made from fruit and vegetables: Bananatex®, Piñatex®, Mylo™, Orange Fiber, Vegea, and Parblex™. Regarding Bananatex®, which developed as the world's first durable, waterproof textile material made purely from the stalks of banana plants. Piñatex® is a vegetable alternative to leather made with pineapple leaves that traditionally are discarded or burned. In this process, no chemical substances are involved in the production, and the process is closed loop because residual biomass is used as a natural fertilizer.

As we have seen during the development of this book chapter, many industrial applications can be developed for each of the waste generated on the planet. Thus, we can carry out the objectives of the circular economy.

6.2 Product Developed with Using FVWs as Food Additives

Currently, the consumption of healthy food is vitally important for lifestyle. In this context, the demand for functional food has increased over the past years. According to Rincón-Leon (2003), functional food is defined as "*food that has a positive impact on an individual's health, physical performance, or state of mind, in addition to its nutritious value*." The American Dietetic Association has defined functional food as "*whole, fortified, enriched, or enhanced" food which is consumed as* ". . . part of a varied diet regularly, at effective levels" (Lau et al. 2021). In recent years, the development of functional foods has further with adding one or more compounds, which could provide multiple health benefits. The incidence of chronic diseases is a significant concern worldwide, affecting human health. Recently, several works have focused on found bioactive compounds from FVWs, principally from tropical fruits, to develop functional food or nutraceutical with different chronic targets (De la Luz Cádiz-Gurrea et al. 2020; Lau et al. 2021). Examples have been used as ingredients in food preparation, such as bread, biscuits, noodles, dairy products, fortified drinks, and juice, among others (Lau et al. 2021).

6.2.1 Bread, Biscuits, and Snacks

Bread is part of the daily diet, so there is a growing interest in incorporating functional ingredients on bread to respond to consumers' demands for healthy foods (Martins et al. 2017). Although, on the other hand, children eat a lot of biscuits, cookies, and snacks, these products are mostly low in nutritional values, such as fiber, protein, and minerals. Incorporating vegetable and fruit by-products increased the product's nutritional values (Lau et al. 2021). Therefore, it is necessary that these types of products also contain healthy ingredients in their composition and synthetic additives, replaced by natural additives present in FVWs.

Bread, biscuits, and snacks have all been made with various FVWs. For example, white bread was made with a dietary fiber produced from soybean and chickpea husks (Niño-Medina et al. 2019). In addition, defatted flax seed from cold pressing extraction oil was used as functional ingredients to enrich wheat flour with bioactive carbohydrates (Belc et al. 2020). Other FVWs used are the orange, pomegranate, elderberry, and spent yeast by-products to fortify wheat bread. The results showed that the consumer preferences contained the following by-product proportion 7.0% elderberry, 2.5% orange, 5.0% pomegranate, and 2.5% spent yeast of the high fiber fraction (Martins et al. 2017).

Unripe bananas are of interest because commercial farms use them as a source of starch. These starches can be changed into resistant forms to slow digestion and lower the glycemic index. Resistant starches are applied in research for reducing diabetes, obesity, and cardiovascular disease (Dhull et al. 2020). Unripe bananas have been utilized as flour in bread formulation, which confer many health benefits to diabetics or celiacs because a low-glycemic index and gluten-free bread are obtained (Dhull et al. 2020). On the other hand, overripe banana has been discarded due to their low quality and appearance. However, a recent study used this fruit waste as a source of natural sweetener and dietary fiber, making chocolate cookies with a low glycemic index (Ng et al. 2020). In a revision presented by Lau et al. (2021), numerous works show cookies and biscuits with FVWs such as soybean hulls, potato peels fiber, grape pomace, pomegranate peel, or apricot kernels, among others.

6.2.2 Dairy Products

The European Union (EU) total milk production is estimated at around 155 million tons per year. The main producers are Germany, France, Poland, the Netherlands, Italy, and Spain (European Union 2021). EU milk global and internal demand continues to grow, although to a lesser extent due to the effects of the recent pandemic due to COVID-19 (USDA 2020). In this sense, new and functional dairy products could be developed incorporating FVWs. Recently in the review by Lau et al. (2021), some examples are presented: cheeses, yogurts, or salads with grape pomace incorporated in their formula or ice cream with tomato or pomegranate peel used as natural colorants and source antioxidant compounds.

6.2.3 Fortified Drinks and Juice

The growing health concern has led to increased consumption of healthy foods and beverages. In these senses, an opportunity is the production of drinks and/or juices fortified or functionalized with FVWs (Corbo et al. 2014). The drinks and juices are the most active functional foods category because of (i) convenience and the possibility to meet consumer demands for container contents, size, shape, and appearance; (ii) ease of distribution and better storage for refrigerated and shelf-stable products; and (iii) great opportunity to incorporate desirable nutrients and bioactive compounds (Corbo et al. 2014).

Anthocyanins are abundant in purple corn. Many anthocyanin-rich co-products are produced during corn processing. Colored corn is becoming a popular source for anmthocyanins extraction (Luna-Vital et al. 2017). Luna-Vital et al. (2017) published a study in 2017 that found purple corn pericarp pigments can be employed in acid beverages with an acceptable shelf life. In the same year, extract from banana peel was used as an antioxidant source in orange juice; the results concluded that in concentrations less than 10 mg of banana peel extract per ml of orange juice, no undesirable changes in the sensory characteristics (in-mouth sensations and color) of the beverage (Ortiz et al. 2017a).

In the same way, the banana peel extract was used to stabilize the antioxidant capacity and sensory properties of orange juice during pasteurization and refrigerated storage (Ortiz et al. 2017b); the banana peel extract was added to freshly squeezed orange juices and orange juices concentrate. Mild pasteurization increased shelf life in refrigeration for both types of orange juice, although orange juice concentrate was more stable than squeezed orange juice. Antioxidant activity of pasteurized enrichment with banana peel extract juices tends to have greater antioxidant capacity over time. When the sensory test was carried out, the panelists found the juices with banana peel extract were more acceptable than conventional ones. However, some modifications became more evident over time (Ortiz et al. 2017b).

7 Conclusions and Future Perspectives

According to the bibliographic review and the antecedents presented, it is evident that FVWs represent an excellent opportunity for isolation of natural food additives with potential food industrial applications. Besides, the FVWs suppose an environmental problem, so the authorities are promoting strategies to reduce them through different directives. In this way, it is possible to achieve the main objectives proposed in the model proposed by the circular economy. Therefore, the reuse of FVWs would imply obtaining an economic and environmental benefit. This chapter showed the different alternatives to take advantage of the FVWs; these products are low-cost raw materials and represent a resource that can be used by industry or society.

Further discussion has been made on the studies on isolating bioactive compounds from specific waste such as fruits (pineapple waste, grape waste, banana waste) or vegetables (potato peel waste, etc.). However, more work needs to be done related to the waste generated by the food processing industries or obtained in the kitchens of restaurants, hotels, and even household waste where there are mixtures of garbage that are difficult to separate. Another interesting work focuses on utilizing FVWs (rich in pectin, fiber, lignin, cellulose, and hemicellulose) to produce novel biodegradable bioplastics. On the other hand, continuing with functional beverages could also be a field to continue innovating. Finally, it is necessary to continue raising awareness among citizens, industries, and governments of the opportunities FVWs offer without forgetting to continue with studies related to optimization of the isolation, extractions, processing, and industrial scale in the future.

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Chapter 3
Drying and Extraction Approach for Utilization of Vegetable and Fruit Waste

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Abstract Reducing food losses along the food chain system could have a positive impact on food security, economic growth, and also the climate. Fresh vegetables and fruits are highly perishable products and hence contribute to higher food waste compared to other commodities. This chapter identifies the potential utilization of vegetable and fruit waste based on its nutritional characterization and the appropriate technological approach for the conversion of food wastage into value-added products. The value addition of these wastes by drying technologies and extraction methods to preserve the desirable attributes can help to facilitate effective food production and can be an alternative market option for other associated industries.

Keywords Drying · Extraction · Fruit waste · Vegetable Waste · Utilization

1 Introduction

In agricultural system, food supply chain (FSC) is a common system that has been used globally to describe how food from cropland ends up on our table. Generally, FSC is divided into five process steps, which are production, post-harvest, processing, distribution and consumption, with food loss and waste occurring at each stage (Parfitt et al. 2010). The loss and waste were due to the unintended consequences of the FSC framework. On the other hand, it is forecasted that a

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growing population will result in 50% rise in food demand by 2050 (Chávez-Dulanto et al. 2021). Thus, reducing food loss and waste through utilization process is seen as an alternative way to improve food security, and they could contribute positively toward Sustainable Development Goals (SDG 12) through responsible consumption and production patterns. Furthermore, it can enhance economic productivity and create significant environmental impacts.

The fruit and vegetable commodity has been identified as the one that generates most food waste (Sagar et al. 2018). The perishable food waste is high due to overproduction; mechanical damage during post-harvest handling; damage by microorganisms, insects, or pests; due to lack of proper storage facilities; and product discarded due to inferior acceptable quality (Nanda et al. 2015; Parfitt et al. 2010; Salim et al. 2017). By-products and residues from food manufacturing and processing industries such as the skin, stalk, pulp, peel, seed, etc. generate 10%–75% of waste materials, which often are high in nutrients (Sagar et al. 2018). Table 3.1 shows some examples of by-products from fruits and vegetables that

Table 3.1 An overview of fruit and vegetable commodity and its by-product health-promoting properties

Commodities	By-products	Health-promoting properties	References
Kiwi	Pomace	Phenolics and antioxidant	Sanz et al. (2020)
	Peels	Phenolics, carbohydrates, mineral, vitamin C, dietary, chlorophylls, carotenoids	
	Leaves, seeds	Phenolics, antioxidant	
Pomelo	Peel	Flavonoids, carotenoids, phenolics, coumarins, organic acids, polysaccharides	Tocmo et al. (2020)
Cantaloupe melon	Peel	Potassium, phenolics, anti-oxidant, chlorophylls	Fundo et al. (2018)
	Pulp	Phenolics, vitamin C, carot-enoids, vitamin A	
	Seeds	Potassium, phenolics, antioxidant	
Broccoli	Stalk, leaves	Phenolics, antioxidant, vita-min carotenoids, glucosinolates, flavonoids	Aires et al. (2017), Bekhit et al. (2013), Domínguez-Perles et al. (2010) and Md Salim et al. (2019)
Tomato	Stems, leaves	Phenolics, antioxidant	Aires et al. (2017)
	Peel	Pectin, polyphenols, fatty acids, flavonoid	Azabou et al. (2020) and Grassino et al. (2020)
Potato	Pulp, peel	Phenolics, antioxidant	Singh et al. (2011), Singh et al. (2020) and Venturi et al. (2019)
Green bean	Stems, leaves	Phenolics, antioxidant	Aires et al. (2017)
Mango	Peel, paste	Phenolic, carotenoids	de Ancos et al. (2018)

still contain nutritional ingredient in them. Hence, exploration on the possibility for utilization of these wastes is needed not only for providing more food to population, but it can also improve the sustainability of healthy diets, economically profitable and reduce the environmental footprint.

2 Drying of Vegetable and Fruit Waste

Drying is a well-known method of preservation because it significantly reduces water activity, thereby preventing bacterial growth. Therefore, it is a most essential step in waste exploitation. Different drying technologies stipulate different drying mechanisms, which results in a variation of food products with different food qualities. Consequently, proper selection of dryer is crucial in the development of dried products to achieve the desired goals in the drying process as presented in Fig. 3.1. Baker (1997) suggested the following procedure for selecting the most appropriate dryer types:

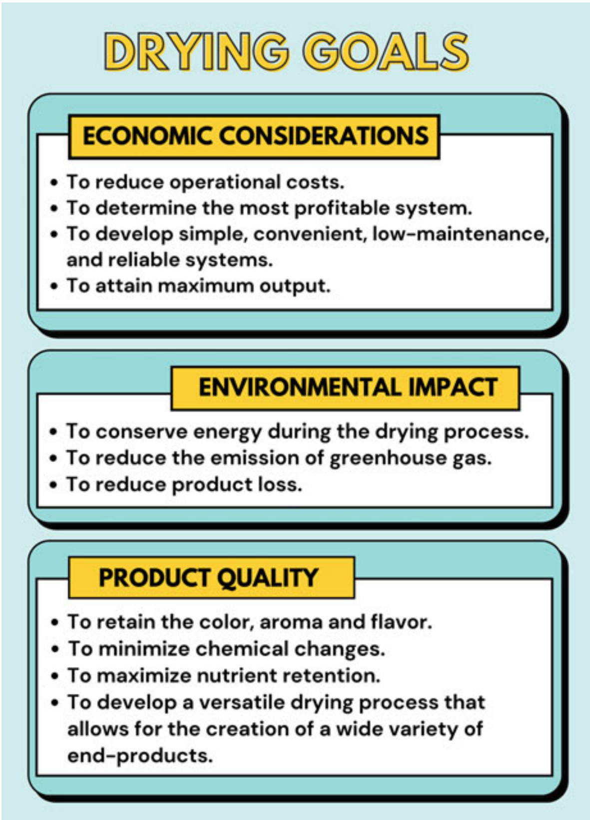

Fig. 3.1 Goals in food drying

1. Make a list of all essential process requirements.
2. Construct a preliminary selection.
3. Run lab-scale tests.
4. Execute economic evaluations.
5. Conduct pilot scale test.

When biological products are exposed to high temperatures for extended periods of time during drying, they frequently degrade in quality and incur high energy costs. Therefore, there exist varied improved drying technologies in food application nowadays. Hybrid drying is one of the promising options to meet the demands of the food industry. Typically, hybrid drying combines two or more drying methods in one process. Recently, a large and growing research reported on various combinations of drying methods for the development of dehydrated fruits and vegetables (Köprüalan et al. 2021; Liu et al. 2020; Seremet et al. 2020).

2.1 Hot Air Drying

Hot air drying is a frequently used method in the drying process due to its simplicity of operation and least expensive. Numerous studies on the development of dehydrated food products using hot air drying have been conducted (Mishra et al. 2021; Ouyang et al. 2021). Recently, a study reported on orange peel dried under hot air impingement dryer results in better preservation of polyphenols, ascorbic acid, and the antioxidant capacity when dried at temperature of 65 °C (Deng et al. 2020). The oven drying method also has been proven as the best drying method for preservation of volatile compounds of fresh mango peel when dried at a temperature of 45 °C for 18 h (Oliver-Simancas et al. 2020). In spite of that, drying with only hot airflow at high temperature may result in quality degradation of dried products especially for heat-sensitive food products. For example, Qing-guo et al. (2006) found that drying edamame (vegetable soybean) under hot air drying at 70 °C resulted in a decrease in vitamin C and chlorophyll content, as well as significant shrinkage and poor rehydration. Politowicz et al. (2018) found that hot air drying is not the best approach for drying mushrooms as more volatile compounds were degraded due to longer drying time. An attempt was done by Das and Arora (2018) to obtain optimal drying for mushrooms, and they found that a combination of microwave and convective hot air drying met the quality standards of commercial dried mushrooms in a short period of time.

2.2 Microwave Drying

Microwave drying is a volumetric drying method that can reduce the drying time and improve the final quality of the dried products. The rapid energy dissipation throughout the material is an advantage to overcome the limitation of other slow drying processes and improves the final quality of the dried products (Zielinska et al. 2020). In a previous study, the aroma of dried celery stalk was found to be high when it was dried using a combination of microwave and hot air drying (Chen et al. 2020). A combination of microwave drying with vacuum drying has also been successfully employed in the drying of various agricultural products (Dash et al. 2021; Monteiro et al. 2020; Shu et al. 2020). A recent study found that microwave vacuum drying of orange peels resulted in high retention of vitamin C, total phenolic, and total carotenoid content (Bozkir et al. 2021). Microwave vacuum drying is also often used in conjunction with hot airflow for water evaporation of heat-sensitive material. This hybrid drying strategy applied on mango slices resulted in a porous structure and high color retention of dried product while compared to microwave vacuum drying alone (Pu and Sun 2017).

2.3 Freeze Drying

In comparison to other dehydration techniques, freeze drying is widely recognized as an excellent dehydration technique for heat-sensitive fruits and vegetables. This is due to the low drying temperature used and the fact that there is almost no oxygen involved in the drying process (Zhang et al. 2006). When samples are dried using freeze drying, the structural rigidity of the samples is maintained due to the frozen substance present at the surface where sublimation takes place. This prevents structure collapse and results in a preserved porous structure as well as non-shrinking dehydrated products (Ibarz and Barbosa-Canovas 2003). It has also been reported that freeze-dried products have a rehydration ratio that is up to six times higher than that of air-dried products (Ratti 2001). Moreover, this drying method has also been reported to produce high retention of polyphenolic characteristics and color attributes in kinnow peel (Rafiq et al. 2019) and pomegranate aril (Adetoro et al. 2020) while compared with other drying techniques. However, this drying technique requires a longer drying time, which results in increased energy consumption and capital costs(Louka and Allaf 2002). Therefore, an attempt has been made to overcome this through combination technique with microwave drying (Hao et al. 2014; Jiang et al. 2010; Wang et al. 2009). Wang et al. (2010) discovered that drying time for potato slices was reduced by 33% when using the microwave-assisted freeze drying compared to stand-alone freeze drying, and these two methods provide comparable vitamin C, sugar, and starch losses.

2.4 Fluidized Bed Drying

Frequently, the technique of fluidized beds that involve airflow passing through the bed of particles is used for drying the particulate product. This drying method is particularly efficient and time-saving because of the intense heat and mass exchange that occurs at the particle surface as a result of the constantly renewed boundary layer. However, it has a significant disadvantage in drying porous materials due to its low energy efficiency and long drying time during the falling rate period (Chen et al. 2001). Microwaves in combination with a fluidized bed are considered an effective way to overcome this limitation. Microwave-assisted fluidized bed drying has been shown to significantly shorten the drying time of peppercorn by up to 90% when compared to conventional fluidized bed drying while retaining the physical texture and color (Kaensup and Wongwises 2004). Zahoor and Khan (2021) reported that red bell pepper dried using microwave-assisted fluidized bed at microwave power of 468.04 W, air temperature of 60.14 °C, and air velocity of 16.82 m/s resulted in better retention of the total phenolics.

2.5 Pre-treatment Methods

Over the past decades, there has been a growing interest in the pre-treatment process prior to drying with the goal of expediting the drying process and enhancing the quality of the finished product. Pre-treatment such as blanching, pulsed electric field, freezing, ultrasound, and osmotic dehydration used in conjunction with drying process may exhibit diverse effects on the final products. For example, blanching pre-treatments prior to drying at a temperature of 60°C were found to have better retention of total phenolic content and the greenness of cabbage (Sarkar et al. 2021). Meanwhile, applying a pulsed electric field as pre-treatment to strawberries and bell peppers prior to freeze drying reduces shrinkage and improves rehydration capacity (Fauster et al. 2020). Freezing as a pre-treatment for convective air drying resulted in improved texture, total phenolic content, and antioxidant activity of dried grapes (Noshad and Ghasemi 2020). Ultrasound pre-treatment is commonly reported as a technique that can result in better color preservation in dried product such as spine gourd (Kumar et al. 2020). For many years, numerous studies have been conducted in utilization of osmosis phenomenon prior to drying process due to its simple and energy-saving process. Table 3.2 presents the effects of osmotic dehydration pre-treatment on different drying techniques used in the production of dried products over the last five years.

3 Extraction of Bioactive Components from Vegetable and Fruit Waste

Any extraction technique has a goal to provide maximum recovery of the bioactive components with technically and economically viable alternatives which makes the selection of appropriate technique crucial. Conventionally, Soxhlet extraction,

Table 3.2 Effects of osmotic dehydration pre-treatment on different drying techniques used in production of dried products in the last five years

Dehydrated product	Hybrid drying approach	Remarks	References
Dried strawberry	Osmotic-freeze drying	Reduction in drying time, better retention of the mechanical and structural properties	Prosapio and Norton (2017)
Dried broccoli stalk	Osmotic-microwave hot air drying	Better quality retention of vitamin C content, chlorophyll content, and total phenolic content when dried at a drying temperature of 40 °C	Md Salim et al. (2019)
Dried pomegranate arils	Osmotic-convective-vacuum microwave drying	Improved the rehydration rate, antioxidant capacity, color, and sensory profile	Cano-Lamadrid et al. (2017)
Dried pumpkin	Osmotic-microwave vacuum drying	Increased in polyphenolic compounds and antioxidant capacity	Lech et al. (2018)
Dried peas	Osmotic-convective drying	Better product quality in terms of moisture content, color, hardness, rehydration ratio, and sphericity	Kaur et al. (2020)
Dried goji berry	Osmotic-air drying	Reduction in drying time, high retention in color, improved texture characteristics, high antioxidant capacity, and total phenolic content	Dermesonlouoglou et al. (2018)
Dried sweet corn kernels	Osmotic-vacuum microwave drying	Improved taste, jucier, and less crunchy	Castillo-Gironés et al. (2021)

solvent extraction or maceration, and hydro distillation are common techniques used for the extraction of bioactive components from the fruits and vegetables' cellular structures.

3.1 Soxhlet Extraction

The Soxhlet method utilizes solvent at boiling temperature and low pressure for the extraction of the targeted bioactive components. Through this extraction technique, a small amount of the sample material either in dried form or wet form is placed in a thimble, and the solvent is continuously passed through the material until the solvent becomes colorless which indicates the completion of extraction. This method of bioactive extraction is simple and easy to use but requires extensive time and consumes a large amount of solvent, which ultimately increases the cost of the process. At the same time, high-temperature processing at a longer extraction time leads to the degradation of thermolabile components and gives a poorer quality of the product (Ngamwonglumlert et al. 2017).

3.2 Solvent Extraction

Contrary to Soxhlet method, maceration or solvent extraction is performed at a lower temperature, with or without continuous agitation. In this extraction process, the sample is used in dry powdered form which increases the surface area for diffusion of the solvent into the matrix and complete extraction of the components with long exposure with the solvents. White grape skin macerated with methanol yields a total phenolics of about 26.7 mg of gallic acid equivalent (GAE), which is nearly similar attained by Soxhlet with 25.6 mg of GAE (Hrnčič et al. 2019). Extraction on dry tomato waste powder with maceration process using hexane/ethanol as a solvent gave a higher yield of carotenoids with effective steeping effect and proved to be a simple process for the extraction, but higher extraction time is the major drawback of this technique (Nour et al. 2018).

3.3 Hydro Distillation

Hydro distillation is also considered a conventional method of extraction which uses distilled water and boiling water/steam for the extraction of bioactive components from biological materials. Three physicochemical processes are involved during the extraction using hydro distillation—hydrolysis using water, diffusion of the water into the cellular matrix, and decomposition of the bioactive into the extraction medium (Soquetta et al. 2018). There is no solvent used during the hydro distillation extraction, so it is considered a clean and green method to separate the volatile and nonvolatile organic components in a single step, while the non-soluble organic components are separated in boiling water. This extraction technology is simple, safe, and easy but utilizes high energy and consumes more time as compared to other conventional methods (Barba et al. 2016).

3.4 Novel Extraction Methods

However, the limitations of conventional extraction technologies such as high use of petrochemical organic solvents, high treatment temperature, long extraction time, high cost of downstream processing to remove the solvents from the extracts, and toxic residues of solvents remaining in the extract have stimulated the development of novel extraction technologies. To overcome these challenges, novel and emerging technologies will provide better extraction efficiency, reduce the equipment size and control the process parameters such as time and temperature, and make it an energy-effective process. Moreover, clean and green technologies will help in the reduction or elimination of the use of organic solvents, as well as the reduction of extraction temperature and time in order to prevent the degradation of thermosensitive components.

3.4.1 Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) is a novel extraction technology that combines microwave radiation and solvent extraction techniques to extract the components from the cellular biological matrix. The technique of MAE involves microwaves that are the electromagnetic fields present in the frequency ranging from 300 MHz to 300 GHz and uses this frequency range to heat the extraction medium. In this frequency range, the waves are made up of two fields that are magnetic field and electric field which are oscillating in nature and are perpendicular by the mechanisms of dipole rotation and ionic conduction (Kwon et al. 2003). Ionic conduction and dipole moment mechanisms help in rapid heating of the extraction solvent and cause cellular disruption due to increase in pressure within the cellular material due to swelling. This disruption helps in the diffusion of extraction solvent into the biological material and helps in moving out the component in solvents (Routray and Orsat 2012). This method has been increasingly used as the specific feature of interaction between solvents and microwave radiations, and it also allows the significant enhancement of the extraction efficiency, less solvent usage, low thermal gradient, and low extraction time (Strati and Oreopoulou 2014). Table 3.3 represented the MAE used for the extraction of bioactive components from the fruits and vegetable by-products with the operating conditions and extraction yield of the components.

3.4.2 Ultrasound-Assisted Extraction

Ultrasound-assisted extraction (UAE) an emerging green extraction technology uses sound waves in the frequency range of 20 kHz to 100 MHz. When an extraction solvent in contact with a sample is subjected to ultrasounds, cavitation phenomenon occurs which provides a greater solvent penetration into the sample, causing pressure and temperature changes (Pacheco-Fernández and Pino 2020). This technique enhances mass transfer, decreases extraction temperature and time, and accelerates the kinetics of extraction solvent with an increase in yield of components (Tiwari 2015). Commonly, UAE is widely applied for the extraction of high-value components such as pectin, dietary fibers, phenolic compounds, flavonoids, natural pigments, and antioxidants from biological materials (Chemat et al. 2017). Table 3.4 summarizes the major extraction parameters of UAE used for the extraction of bioactive components from the fruits and vegetable by-products with effective extraction yield.

Table 3.3 Microwave-assisted extraction used for the extraction of bioactive components from fruit and vegetable by-products

Fruit/vegetable by-products	Bioactive component	Operating conditions	Extraction yield	References
Sour cherry pomace and marasca	Anthocyanin, phenolic compounds	Temperature: 60–70 °C, power: 400 W, irradiation time: 10 min, solvent (80% methanol in water)	Increased extraction yield of polyphenols compared to conventional extraction.	Garofulić et al. (2013)
Black carrot pomace	Anthocyanin, phenolic compounds, antioxidants	Power: 348 W, time: 10 min, ratio solid to solvent: 1:20, solvent: Ethanol (20%)	The maximum yield of anthocyanin and phenolic compounds was observed in comparison to conventional extraction.	Kumar et al. (2019)
Tomato peels	Lycopene	Ratio solid to solvent: 1:10, power: 400 W, time: 1 min, solvent: Ethyl acetate	Lycopene yield of 13.59 mg/100 g tomato waste was observed.	Ho et al. (2015)
Grape skin	Polyphenols, anthocyanin	Power: 540 W, time: 3 min, temperature: 100 °C, solvent: 50% ethanol in water	13–16% recovery of polyphenols.	Liazid et al. (2011)
Carrot waste	β-Carotene, lycopene, antioxidants	Power: 180 W, ratio solvent mixture of hexane: Acetone: Ethanol: 2:1:1	The maximum yield of carotenoids and antioxidants was observed as compared to Soxhlet extraction.	Hiranvarachat and Devahastin (2014)
Lemon peels	Total phenols	Power: 400 W, solvent: 48% ethanol, time: 123 sec	Total phenolic content: 1574 mg GAE (gallic acid equivalent)/ g d.b.	Rodríguez García and Raghavan (2021)
Banana peels	Total phenols, pectin	Power: 960 W, solvent: 100% water time: 6 min, ratio solid to solvent: 2:100	Total phenolic content: 50.55 mg GAE/ g d.b.	Vu et al. (2018)
Potato peels	Phenolic content, antioxidants	Power: 960 W, solvent: 60% ethanol in water temperature: 80 °C, time: 2 min, ratio solid to solvent: 1:40	Total phenolic content: 11-15 mg GAE/ g d.b.	Li et al. (2012)

Table 3.4 Ultrasound-assisted extraction (UAE) of bioactive components from fruit and vegetable processing by-products

Fruit/vegetable by-products	Bioactive component	Operating conditions	Extraction yield	References
Carrot waste	β-Carotene, antioxidants	Solvent: Vegetable oils, temperature: 50 °C, time: 50 min, power: 100 W, frequency: 20 kHz	Increased yield of β-carotene in the range of 83.32% was observed.	Purohit and Gogate (2015)
Tomato processing waste	Lycopene, antioxidants	Solvent: Hexane: Ethanol: Acetone (2:1:1), temperature: 60 °C, time: 40 min, power: 90 W	Increased recovery of lycopene was observed with UAE in comparison to conventional techniques.	Kumcuoglu et al. (2014)
Grape pomace	Anthocyanin, phenolics, flavonoids, antioxidants	Solvent: Water, temperature: 45 °C, time: 20 min, power: 100 W	70 mg/100 g waste anthocyanin content and 70% antioxidants were obtained.	Tiwari et al. (2010)
Grape by-products	Polyphenol, antioxidants	Solvent: Water, temperature: 70 °C, time: 1 min, frequency: 35 kHz	50% more yield was observed compared to conventional extraction.	Barba et al. (2016)
Mango peel	Phenolics, flavonoids	Solvent: Ethanol, temperature: 30 °C, time: 20 min, frequency: 20 kHz	The total phenolic content of the extract increased with UAE.	Guandalini et al. (2019)
Grapefruit waste (pomace, seeds, peels)	Phenolics, flavonoids, antioxidants	Solvent: Ethanol, temperature: 25 °C, time: 55 min, frequency: 40 kHz, power: 100 W	Increased content of total phenolics and antioxidants was observed.	Garcia-Castello et al. (2015)
Pomegranate (peels, pomace)	Phenolics, carotenoids, flavonoids, antioxidants	Solvent: Ethanol, ratio solid to solvent: 1:20, temperature: 25 °C, time: 55 min, frequency: 20 kHz power: 100 W	Phenolics content increased with UAE by 24% and time reduced by 90%.	Pan et al. (2012)
Olive leaves	Phenolics, carotenoids, flavonoids, antioxidants	Solvent: Ethanol, ratio solid to solvent: 1:20, temperature: 40 °C, time: 20 min, frequency: 40 kHz, power: 100 W	40% increase in phenolic content and 30% antioxidant content increased.	Şahin (2015)

3.4.3 Pressurized Liquid Extraction

Pressurized liquid extraction (PLE) also known as accelerated solvent extraction or pressurized fluid extraction involves the separation of solutes from the solid matrix of biological material at elevated temperatures and pressures up to 200 bar (Soria et al. 2012). This elevated temperature and pressure reduce the surface tension and viscosity of the solvent, disrupt the cell material, and thus help in easy penetration of the solvent into the solid matrix which further increases the mass transfer (Mustafa and Turner 2011). As represented in Table 3.5, PLE using water and/or ethanol as solvent has been successfully used to extract thermally sensible phytochemicals from many fruit and vegetable residues.

3.4.4 Supercritical Fluid Extraction

Supercritical fluid extraction (SFE) works on the principle of change in temperature and pressure of the fluid to achieve its critical temperature and pressure where the liquid and gas phase of the extraction phase is indistinguishable. When the material is fed to the critical temperature and pressure, the supercritical conditions occur and help in an increase in diffusion, solubility, and mass transfer (Ibáñez et al. 2016). Supercritical fluids such as supercritical carbon dioxide (SC-CO_2) have lower viscosity and surface tension which helps them in easy penetration of solvent into the solid matrix and increases the extraction efficiency. For example, a previous

Table 3.5 Pressurized liquid extraction of bioactive components from fruit and vegetable processing by-products

Fruit/ vegetable by-products	Bioactive component	Solvent	Operating conditions	References
Blackcurrant	Polysaccharides	Water	Temperature: 52 °C, time: 51 min, pressure: 1.6 MPa	Xu et al. (2016)
Blackberry peel and seeds	Anthocyanin, phenolic compounds, and antioxidants	Water, acidified water: Ethanol (1:1)	Temperature: 100 °C, time: 10 min, pressure: 25 MPa	Machado et al. (2015)
Peppers	Capsaicinoids	Water	Temperature: 200 °C, time: 10-20 min, pressure: 20 MPa	Bajer et al. (2015)
Pomegranate peel	Total phenolic content, punicalagin content, and antimicrobial activity	77% ethanol	Temperature: 200 °C, time: 20 min, pressure: 1500 psi	García et al. (2021)
Olive pomace	Phenolic compounds	52.3% ethanol	Temperature: 136.5 °C, time: 20 min, pressure: 1500 psi	Cea Pavez et al. (2019)

study reported that the levels of lutein and lycopene in pumpkin were significantly higher in SC-CO_2 extracts than in organic solvent extracts (Shi et al. 2010). The optimum conditions for obtaining 86.1% carotenoid recovery from carrot peels by SC-CO_2 were found to be 59.0 °C, 349 bar pressure, and 15.5% ethanol as co-solvent, conditions that are very similar to those that apply for mass yield (de Andrade Lima et al. 2018). The SFE technique was also reported to be successful in adding value to potato peels, with a total phenolic recovery of 37% and an 82% caffeic acid recovery under optimized process conditions of 80 °C, pressure of 350 bar, flow rate of 18.0 g/min, and methanol of 20% (de Andrade Lima et al. 2021).

3.4.5 Enzyme-Assisted Extraction

Another novel technology employed for the extraction of bioactive components is enzyme-assisted extraction (EAE). EAE is an eco-friendly safe alternative to conventional extraction technology as it uses natural enzymes and water as a solvent instead of organic and petrochemical solvents. The cell wall of biological material contains polysaccharide materials such as pectin, cellulose, and hemicellulose which provide a barrier for the removal of intercellular components. Hence, enzymes can be used for the breakdown of cell wall material which further facilitates the extraction of intercellular components. This extraction methodology was also used as a pre-extraction step in MAE, UAE, SFE, and PEF to improve extraction. The factors responsible for the better extraction efficiency of EAE are particle size of material, enzyme concentration, solid to liquid ratio, the composition of the material, and hydrolysis time. This technology has gained interest in the extraction of various bioactive components such as polyphenols, carotenoids, anthocyanin, pectin, and flavonoids. The major bioactive component extraction using EAE from fruit and vegetable by-products are listed in Table 3.6. Irrespective of all the benefits of this clean technology, there is only one limitation associated with this process which is the cost of the enzymes leading to a costly process. But immobilization technique provides a solution to this problem by reusing the enzymes without loss in cellular activity and specificity (Xu et al. 2018).

4 Conclusion and Perspective

Waste reduction and utilization of resources have become a precedence due to environmental and sustainability concerns. Thus, the excess of by-products and residues generated from fruit and vegetable management systems which have the potential to be a source of healthy compounds need to be valorized. Transformation of this valuable resources into high value-added products that are of interest in the

Table 3.6 Enzyme-assisted extraction of bioactive components from fruit and vegetable processing by-products

Fruit/ vegetable by-products	Bioactive component	Enzyme	Operating conditions	References
Grapes peels, skin, and pomace	Polyphenols: Gallic acid, catechin, gallocatechin, vitamin: Tocopherol	Pectinase, xylanase, and β-glucanases	Temperature: 35 °C, time: 24 h, pH: 5.5, solvent: 0.1 M sodium acetate buffer, agitation: 100 rpm	Chamorro et al. (2012)
Olive waste	Total phenols and antioxidants	Cellulose, pectinase, and hemicellulose	Temperature: 55 °C, time: 40 min, pH: 5.75, solvent: Ethyl acetate, power density ultrasonic bath: 0.05 W/mL. Ultrasonic frequency: 37 kHz	Wang et al. (2017)
Pomegranate waste	Phenolics: Vanillic, ferulic, and caffeic acid	Pectinase, cellulose, and protease	Enzymatic pre-treatment: Temperature: 49 °C, time: 85 min, pH: 6.7, ratio mixture enzyme: Pectinase: Protease: Cellulose (1:1:2) Supercritical-CO_2 at 55 °C, 300 bar pressure, and 30-120 min	Mushtaq et al. (2015)
Capsicum	Carotenoids, phenolics, ascorbic acid content and antioxidant activity	Pectinase, cellulase, and viscozyme L	Temperature: 60 °C, time: 1 h, pH: 4.5.	Nath et al. (2016)
Tomato waste	Lycopene	Cellulase and pectinase	Temperature: 25 °C, time: 4 h, pH: 4.5-5.0, Cellulase: 1.5%, pectinase: 2%, solvent extraction: Acetone/ ethanol/ hexane	Ranveer et al. (2013)

food, cosmetics, and pharmaceutical industries can be accomplished through the drying and extraction approach. As most biological materials are complex and have their own distinct features, the choice of technology in the drying or extraction process depends on the nature of the material and the process conditions. In the drying process, the development of hybrid drying has become an effective strategy to reduce the drying time and energy consumption while improving the food quality. Meanwhile, implementation of green technologies as alternatives to overcome the limitations of conventional extraction methods is a promising approach in order to obtain higher yields with rapid extraction time. Taken together, innovative processing technology for the valorization of the fruit and vegetable waste not only ensures sustainability and benefits producers and the agro-food industry, but it also has a positive impact on climate change by reducing carbon dioxide emissions.

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Chapter 4
Phenolic and Other Bioactive Compounds from Vegetable and Fruit Waste: Extraction Methods and Their Possible Utilization

Balwinder Singh Sooch, Manpreet Kaur Mann, Priyanka Sharma, and Ramesh C. Ray

Abstract Vegetables and fruits have been considered as one of the most consumed staple foods in society as these possess many health-promoting factors. The enhanced day-to-day demand has fastened their production and processing rate, which generates a plethora of significant fresh and processed vegetable and fruit wastes. Various vegetable and fruit processing practices produce around 20–30% of waste by-products constituted of skin, pomace, seeds, etc. These waste materials are a rich source of many functional bioactive compounds such as polyphenols, vitamins, fibers, enzymes, oils, etc. These phenolic and bioactive compounds can be recovered from vegetable and fruit wastes through several extraction methods. Further, these extracted valuable materials have been valorized into value-added products especially tailored for many pharmaceuticals, health, and food applications. The present chapter focuses on types of vegetable and fruit waste, phenolic and bioactive compounds present in this waste, various strategies from the extraction of these valuable materials, and their possible conversion into functional value-added products.

Keywords Phenolic · Polyphenols · Bioactive · Acids · Organic acids · Fruit waste · Vegetable waste

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1 Introduction

Massive food waste has been considered as one of the most important concerns because many beneficial nutritional supplements get directly scrapped off into dustbins as food waste. Food processing industries generate a lot of solid and liquid food waste containing many valuable components, but the disposal of this waste is causing many pollution problems (Sooch and Singh 2002; Singh et al. 2004). To encounter these detrimental environmental issues caused by food wastage disposal, several strategies can be followed to valorize them into value-added products. According to United Nations Report (2015), Asia will be the highest populated region in the upcoming years. The world population is estimated to increase around 9.7 billion or higher by 2050 (FAO 2011). Food scrapping starts from the initial stages of production to the final distribution to consumers, estimated at around 1.3 billion tons, about one-third of the total food produced (FAO 2011). Worldwide production of different vegetables and fruits in million metric tons (MMT) has been presented in Fig. 4.1. Nearly 1314 trillion kCal in a year can be piled up from scrapped food, which adds to a greater economic help to the food market and proves beneficial in reducing the harmful environmental effects caused by these food waste materials (Foley et al. 2011).

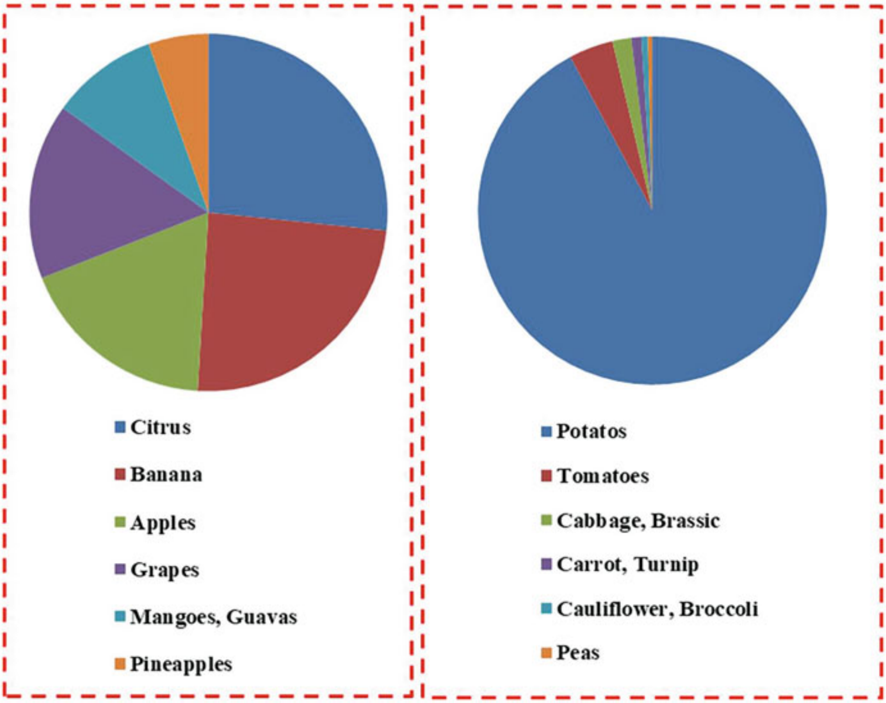

Fig. 4.1 Worldwide production of different vegetables and fruits in million metric tons (MMT)

Vegetables and fruits are the highest waste-producing commodities possessing different residues from cereals (19%), roots and tubers (20%), and peels, pomace, and seeds (25–30%) having worthy nutritional values (Galanakis 2013). Instead of wasting them, these can be utilized for sustainable development by converting them into high value-added products. Almost all sectors contribute to food wastage through processing practices, such as 42% from the household sector, 39% from the industrial sector, and 19% from servicing and distribution sectors (Mirabella et al. 2014). Since time immemorial, biowaste was only utilized as biofertilizer and cattle feed. Still, nowadays, maximum food waste can be utilized entirely to manufacture real-time value-added products in cosmetics, pharmaceuticals, and other industries (Rudra et al. 2015). Fruit and vegetable waste is a very rich source of many phenolic and other bioactive compounds. Bioactive compounds extracted from vegetable and fruit wastes possess many innovative health-promoting and therapeutic benefits, which enhance their further exploration towards sustainability (Ajikumar et al. 2008; Mann and Sooch 2020).

The majority of the waste-producing countries are the Philippines, India, China, and the United States (Schieber et al. 2001; FAO 2014). Several strategies can be followed to extract bioactive compounds from vegetable and fruit wastes, such as phenolic compounds, fatty acids, vitamins, carotenoids, phytosterols, etc. Vegetables and fruits like mango, beetroot, grapes, tomato, pomegranate, beetroot, etc. produce waste in the form of peel, pulp, seeds, and roots, which, when disposed of, become a significant cause of land pollution and air pollution with high emission of methane and carbon dioxide. Food waste contains good carbon and nitrogen content, making the waste a good source of protein and carbohydrates for manufacturing many functional products. From an industrial point of view, food waste has proven a more cheap and efficient energy source due to the presence of valuable bioactive compounds. Hence, the present chapter captures an overview of different types of food waste in terms of vegetables and fruits, extraction methods for phenolic compounds and other bioactive components, and their possible valorization into value-added products, which is an upcoming trending sector in the future.

2 Types of Vegetable and Fruit Wastes

Most of the worldwide agriculture produce generates various types of waste from harvesting to consumption, which goes into dumps. Waste from agricultural produce continues to be drained in different forms, such as stalks and leaves during harvesting and nonedible parts during consumption, including seeds and peels, as shown in Table 4.1. Among all, durian, jackfruit, and citrus fruits are the major contributors to food wastage around 50–70%, whereas on the other hand, guava proved to be the least contributor, about 10% (Saxena et al. 2011; Siriphanich and Yahia 2011).

The fruit juice industry generates solid and liquid waste at different processing stages depending on the type of raw fruits used and the end product formed. It is

Table 4.1 Different types of wastes scrapped from vegetables and fruits

S. no.	Vegetables/ fruits	Scientific name	Types of waste	Bioactive compounds		References
				Classes	Compounds	
1.	Carrot	*Daucus carota*	Peels, pomace	Flavonoids, carotenoids, polyphenols	Saponins, carotenes, tannins	Shyamala and Jamuna (2010) and Nguyen and Scarlett (2016)
2.	Cauliflower	*Brassica oleracea*	Leaves	Flavonoids, hydroxycinnamic acid	Kaempferol, quercetin, caffeic, sinapic acids	Llorach et al. (2003) and Soengas et al. (2012)
3.	Potato	*Solanum tuberosum*	Peels	Phenolic acids, glycoalkaloids	Gallic acid, caffeic, vanillic acid	Zeyada et al. (2008) and Samotyja (2019)
4.	Tomato	*Solanum lycopersicum*	Skin, pomace	Caratenoids, sterols	Sterols, tocopherols, carotenes, terpenes	Strati and Oreopoulou (2011) and Kalogeropoulos et al. (2012)
5.	Apple	*Malus domestica*	Peels, flesh, skin, seeds, stem	Flavanoids, polyphenols	Chlorogenic acid, caffeic acid, ferulic acid, cyanidin-3-O-galactoside, ascorbate	Wolfe and Liu (2003) and Waldbauer et al. (2017)
6.	Avocado	*Persea americana*	Peels and seeds	Polyphenolic compounds, proanthocyanidins	Quercetin glycosides, coumaroylquinic acid, procyanidin dimers of type A and B, catechin, procyanidin trimers of type A, caffeoylquinic acid	López-Cobo et al. (2016) and Araújo et al. (2018)

7.	Citrus fruits		Peels, seeds	Polyphenols, pectin, terpenes, carotenoids	Limonin, nomilin, d- limonene, ferulic acid, naringin, narirutin	Boukroufa et al. (2015) and Esparza-Martínez et al. (2016)
8.	Grapes	*Vitis* spp.	Skin, seeds, pulp	Flavanoids, phenolic compounds, dietary fiber	Proanthocyaninns, catechins, gallic acids, epichatechin	Kammerer et al. (2005) and Aliakbarian et al. (2012)
9.	Mango	*Mangifera indica*	Peels, seeds	Phenolic compounds, carotenoids	Gallic acid, gallates, tannins	Arogba (2000) and Adilah et al. (2018)
10.	Pomegranate	*Punica granatum*	Peels, mescarp, seeds	Anthocyanins, ellagitannins, sterols	Ellagic acid, gallic acid and punicalagin gallic acid, ellagic acid γ-tocopherol daucosterol	Ismail et al. (2012) and Hasnaoui et al. (2014)

estimated that a maximum of 50% content can be recovered in the form of juice from citrus or other fruits. The rest 50% is responsible for waste addition, including pulp, seeds, pomace, etc. (Rezzadori et al. 2012). Although this type of industrial waste was utilized as feed for cattle or as fertilizers, some waste materials generated are poor in protein. Still, rich in lignin, which is indigestible to livestock (Van Dyk et al. 2013), further incineration or dumping in lands leads to environmental disturbances. Various lignocellulosic materials left over after agro-processing can be exploited to manufacture many value-added products like enzymes, alcohol, polyol sugars, silica, etc. (Sooch et al. 2019; Kauldhar et al. 2021). Instead of disposing of such wastes, value-added products can be manufactured via several scientific strategies, which could be possible only through innovative extraction methods for bioactive compounds from vegetable and fruit waste.

3 Phenolic and Other Bioactive Compounds Extracted from Vegetable and Fruit Waste

Bioactive compounds from vegetable and fruit waste generally possess several useful properties like antioxidants, anti-inflammation, and antimicrobial (González-Molina et al. 2010; Johnson 2013). Therefore, these compounds extracted from fruit waste are classified into phenolic compounds and dietary fibers depending on the molecules' identity, as shown in Fig. 4.2.

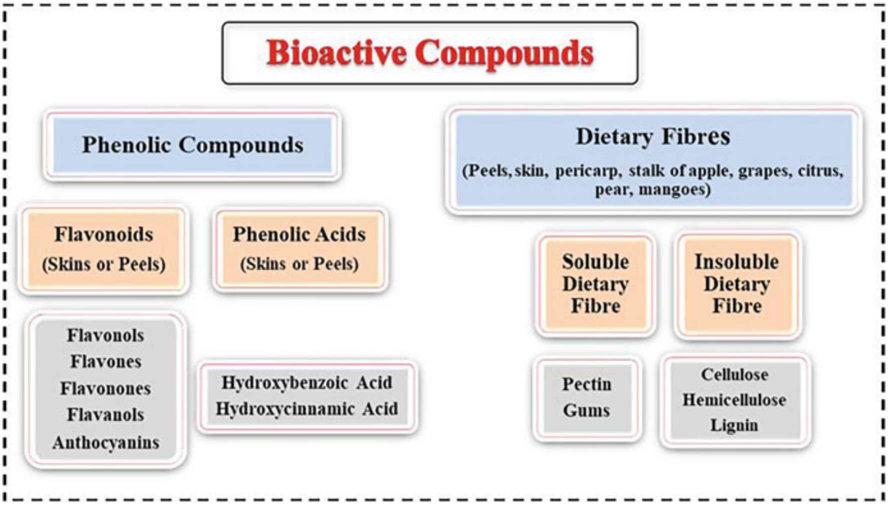

Fig. 4.2 Broad classifications of bioactive compounds from fruits and vegetables

3.1 Phenolic Compounds from Vegetable and Fruit Waste

Phenolic compounds are classified as secondary metabolites and subdivided into acids, flavonoids, and 8000 more subclasses, including tannins, lignins, stilbenes, etc. (Balasundram et al. 2006; Ignat et al. 2011; Gnanavinthan 2013). Phenolic compounds have at least one hydroxyl group attached to an aromatic ring (Balasundram et al. 2006). Among all existing bioactive compounds from food wastes, around 50% are phenolic compounds (Friedman 1997). Glycosides, which impart color to fruits, flowers, and leaves, have also been found in plants and flavonoids (Wu and Prior 2005). The antioxidant property of phenolic compounds directly depends upon the side chain attached to the phenol ring (number of carbon and position of hydroxyl group) (Naczk and Shahidi 2006). Waste materials with phenolic content follow a unique trend in decreasing order. Olive leaves possess the maximum phenolic content, followed by tomato peels, cucumber peels, watermelon, and potato peels. The phenolic content directly depends upon the type of extraction method, but their yield can be further enhanced with improvised technologies (Safdar et al. 2016).

3.1.1 Phenolic Compounds from Vegetables Waste

The vegetable waste includes husk, skin, peels, pomace, etc. Carrot is one among them generating pomace as waste which can be used to extract α- and β-carotene, a very expedient bioactive component. On the other hand, skin from tomatoes contains a significant content of lycopene that can impart color to other edible products (Schieber et al. 2001; Sharma and Le Maguer 1996). Potato waste peels are a rich source of gallic acid and chlorogenic acid (Choi et al. 2016). Onion and garlic waste in skin and husk, respectively, consists of quercetin 3, 4 o-o-diglucoside, and quercetin 40-o-monoglucoside in onion skin hydroxybenzoic acid, D-ferulic acid, caffeoylputrescine, and p-coumaric acid in garlic husk (Kallel et al. 2014). The most common phenolic acids present in potato and tomato waste are chlorogenic acid, gallic acid, caffeic acid, and p-hydroxybenzoic acid (Zeyada et al. 2008).

3.1.2 Phenolic Compounds from Fruit Waste

Consumption of apples, bananas, bilberry, chokeberry, citrus fruits, grapes, kiwifruit, mango, and olives creates waste rich in phenolic and other bioactive compounds. Commonly found phenolic compounds in fruits are catechin, cyanidine, anthocyanidins, carotenoids, caffeic acid, hesperidin, naringin, flavonol, gallic acid, and ellagic acid. Consortia of wastes from a single fruit add up to different bioactive components. In the case of bananas, bract contributes to cyanidin and anthocyanidins, whereas banana peels contribute to carotenoids like xanthophylls, palmitate, and laurate (Pazmino-Durán et al. 2001; Subagio et al. 1996). Grape fruit exhibits three types of waste containing different components: Seeds exhibit procyanidins; pomace yields catechin, anthocyanins, flavonols, and glycosides; and grape skin yields gallate, epicatechin, and catechin (Souquet et al. 1996; Schieber et al. 2001). Mango (*Mangifera indica)* waste consists of peels and seeds, which can be used for the extraction of flavonol, glycosides, gallates, gallotannins, gallic acid, and ellagic acid (Arogba 2000; Schieber et al. 2000, 2001). Apple waste can be exploited for the extraction of bioactive components such as procyanidin, catechin, and hydroxylcinnamates from pomace and chlorogenic acid, cryptochlorogenic acid, and quercetin-3-o-galactosides from leaves (Foo and Lu 1999; Lommen et al. 2000; Teleszko and Wojdyło 2015).

3.2 Other Bioactive Compounds from Vegetables and Fruits

Dietary fibers are mainly cellulose and hemicellulose, but pectin is also present in many other types of fruit skins like apple pomace, grapes, etc. For example, dietary fibers with a maximum of 77.9% are present in grape seed, and a minimum of 3.11% is present in cauliflower stem (Valiente et al. 1995; Femenia et al. 1997). Dietary fibers impart two types of functional properties that help improve the physical and nutritional properties of food. The other includes physiological properties that help reduce cholesterol, balance sugar through insulin level, reduce inflammation, treat piles, and protect against colon cancer (Laurentin et al. 2003). Dietary fibers consist of carbohydrate molecules as soluble dietary fibers, including gums and pectin, and insoluble dietary fibers like cellulose, hemicellulose, and lignin.

3.2.1 Other Bioactive Compounds from Vegetable Waste

Onion contains three types of dietary fibers found in layers; outer layer to inner layer varies in dietary fiber content, which is highest for skin about 68.3%, and innermost containing the least about 11.6% dietary matter (Jaime et al. 2002). Potato peel is also a good source of crude fiber, and potato pulp has a good content of rhamnogalacturonan 1 (Ncobela et al. 2017). Fig. 4.3 shows potato varieties having dietary matter per 100g (Gumul et al. 2011). Non-starchy polysaccharides are obtained from cauliflower waste, and waste types as floret and stem both have variability in dietary fiber. These non-starchy polysaccharides contain pectin. Cauliflower cooking leads to loss of nutrients, but fresh cauliflower leads to lesser loss than frozen cauliflower (Femenia et al. 1997). Carrot pomace consists of a total of 63.6% of dietary matter, which is divided into insoluble fibers (50.10%) and soluble fibers (13.50%) (Idrovo Encalada et al. 2019).

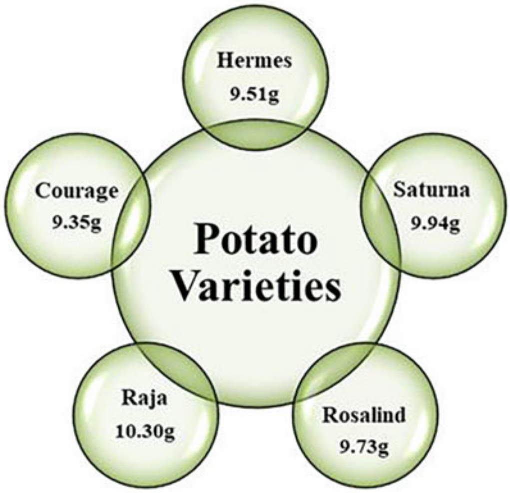

Fig. 4.3 Amount of dietary fibers in various potato varieties (g/100g dry matter)

3.2.2 Other Bioactive Compounds from Fruit Waste

The dietary fiber content in apple peel is around 0.91%, with soluble fibers (0.43%) and insoluble fibers (0.48%). Cellulose, hemicellulose, and pectin are important dietary fibers in grape pomace (Kammerer et al. 2005). The highest dietary fiber is analyzed in the red grape variety named "Tempranillo" (González-Centeno et al. 2010). Around 77.20% of dietary matter is seen in the red grape variety, consisting of 3.77% dietary matter in soluble fibers and 73.50% in insoluble fibers. Red grape pomace consists of richer dietary matter than the white grape, which depends on their variation of pomace constituents. Mango peels have been considered a waste with 51.2% dietary matter total; 19% is soluble fiber, 32.2% is insoluble fiber, and carbohydrates like galactose, glucose, and arabinose are also present (Ajila et al. 2007). Cellulose and pectin polysaccharides are present in oranges around 57% total, with 9.41% soluble fibers and 47.6% insoluble fibers. Peach is another fruit with 30.7%–36.1% dietary fibers with 12.3% soluble fibers and 23.3% insoluble fibers (Chang et al. 2000).

4 Extraction Methods for Phenolic and Bioactive Compounds from Vegetable and Fruit Waste

Extraction of phenolic and bioactive compounds from fruit and vegetable waste comprises of series of critical steps, which determines the quality and recovery content of the extracted bioactive compounds. Extraction methods depend upon the type of bioactive or phenolic compounds to be extracted and on several factors such as type of fruit or vegetable waste, process temperature, type of solvent used, and other processing conditions. The two significant extraction methods to extract phenolic and other compounds from fruit and vegetable waste are conventional and advanced methods.

4.1 Conventional Methods

The conventional methods are the traditional methods that include the basic solvent extraction technique or using heat, or both. Mainly, conventional methods include hydro-distillation, maceration, and Soxhlet extraction technique. Hydro-distillation technique has been anciently employed to extract plant oils and other bioactive compounds, which is further an amalgam of three techniques: distillation, direct steam distillation, and steam distillation (Vankar 2004). It involves packing the waste sample in a static vessel and then a sufficient amount of boiling water or steam is added. Hot water or steam helps in the separation of bioactive compounds from fruit and vegetable waste. The vapor consisting of oil and water is condensed, where bioactive compounds and oil are fragmented spontaneously from water (Silva et al. 2005). It involves three processes such as hydrolysis, hydro-diffusion, and decomposition. It is not applicable for heat-susceptible bioactive compounds as they may be degraded at high-temperature conditions.

Maceration has also been used from ancient times for the preparation of several syrups or extracts. It is an essential cost-efficient technique to extract certain bioactive compounds and essential oils in low quantities. It involves several steps, from grinding vegetable or fruit parts into miniature particles to mixing them with the solvent. Furthermore, a suitable amount of solvent known as menstruum is placed in a closed apartment, followed by discarding the spent liquid and pressing the solid residues. Finally, the pressed liquid is separated through filtration to free it from impurities (Khoddami et al. 2013).

Soxhlet extraction is a famous classical approach widely used to extract bioactive components from various vegetable and fruit wastes. Initially, it was designed by German scientist Franz Ritter von Soxhlet for lipid extraction. A small amount of dry sample is kept in a thimble, placed in a distillation flask containing a suitable solvent. A siphon aspirates the extraction from the thimble holder and fetches it back into the distillation apartment as soon as it reaches an overflow level. The extracted solute stays in the distillation vessel, and the solvent passages back to the solid material repeatedly. This process continues until the complete extraction is achieved.

4.2 Advanced Methods

Although conventional methods have been widely used, certain drawbacks hinder their usage in the extraction process for fruit and vegetable waste. Therefore, many advanced methods have been developed in the past. These methods have many advantages over conventional methods with more efficient ways of high yielding, less time-consuming, and easy operating conditions. Some of the advanced techniques usually used are highlighted below.

4.2.1 Solvent Extraction

It is a cost-effective method and operated efficiently in which organic solvents are used to extract usable compounds, for example, anthocyanins, carotenoids, lycopene, and polyphenols. These extracted compounds have shown their bioactivity against cancer and inflammation (Vyas et al. 2014). Filtration and centrifugation are the two techniques that are used as basics for solid separation for the removal of solid residues. This method is used for thermostable compounds because high temperature is used during downstream. Among solvents, ethanol is maximally used and proved best, and hexane is the minimally used solvent (Bandar et al. 2013). Besides ethanol and hexane, ether, chloroform, acetonitrile, benzene, etc. have also been used along with water in specific ratios. Polar and nonpolar compounds are both extracted via solvent extraction (Plaza et al. 2010). Specific bioactive compounds are extracted with specific solvents, such as ethanol, which mainly extract tannins, flavonol, terpenoids, and alkaloids. In contrast, methanol is used to extract mainly anthocyanins, saponins, flavones, tannins, etc., and finally, these solvents are removed via evaporation. The extraction of phenolic compounds from *Thymus vulgaris* L. was carried out with solvent acetone to water (1:1 (v/v) ratio), and the extract was efficiently used for antioxidant property (Alu'datt et al. 2016). Higher content of phenolic compounds and antioxidants from pineapple peels were extracted at ambient temperature for 25 min using solvent and pineapple peel ratio of 1:1 (w/w) with solvent water/ethanol content of 20:80. The obtained results revealed the total phenolic content of 11 mg GAE/g dry extract using Ferric Reducing Antioxidant Power (FRAP) analysis (Lourenço et al. 2021).

4.2.2 Supercritical Fluid Extract

Supercritical (SC) fluid extraction is an eco-friendly approach mainly used to extract bioactive components from food industry waste and other naturally occurring substances. The supercritical process is carried out using CO_2 at high pressure (200 bar) and 50°C. Supercritical fluids have the density of a liquid and viscosity of the gas, and their diffusivity lies between both liquid and gas (Herrero et al. 2006). Co-solvents like hexane, methanol, ethanol, and dichloromethane are used in lesser amounts with primary solvents to increase the selectivity of the bioactive compounds (Sihvonen et al. 1999). Supercritical carbon dioxide can be used instead of solvents due to its cost efficiency, safety, and solubility in lipophilic compounds, which can be easily separated (Wang and Weller 2006). The sample holder is controlled with temperature and pressure, where the raw material is pumped via a fluid pump to separate dissolved compounds (Sihvonen et al. 1999). This type of extraction is highly used for phenolic compounds such as flavonoids, polyphenols, catechin, epicatechin, tocopherols, etc. It is efficient enough to extract compounds from algae, microalgae, plants, and food waste and is safe for the environment. It can be easily extracted using nontoxic solvents, and specific types of compounds can be extracted. The method mentioned above is now available in food industries for applications like decaffeination of coffee, extraction of essential oils, and refining fats. Optimum conditions are required along with solvents to extract compounds; in the case of carotenoids from tomato paste waste, 5% ethanol is used as co-solvent at the temperature of 88°C and 300 bar pressure, but in case of extraction of anthocyanins from grape seed, 30% ethanol at 30–40°C temperature and 130 bar pressure were used.

Ahmadian-Kouchaksaraie and Niazmand (2017) reported the use of SC-CO_2 for the extraction of antioxidants from *Crocus sativus* petals at optimized conditions (62°C, 47 min, 164 bar). In this process, 1423 mg of phenolics, 180 mg of flavonoids, and 103.4 mg of total anthocyanins were recovered per 100 g total phenolics, flavonoids, and anthocyanins, respectively. Ashraf-Khorassani and Taylor (2004) have used the methanol-modified CO_2 for the extraction of polyphenols and procyanidins from grape seeds, and a good amount of catechin and epicatechin ($>$ 79%) was recovered from the seeds. Wenzel et al. (2016) reported the optimal conditions (68°C and 20% ethanol in SC-CO_2) for good extraction of phenolic compounds from black walnut (*Juglans nigra*) husks. However, another study followed a supercritical fluid extraction technique to recover bioactive compounds and total phenolic content among the beetroot's aerial parts, including leaves and stems. The highest yield of the total phenolic content of 99 mg GAE/g from leaves and 98 mg GAE/g from stems was obtained through this supercritical fluid extraction technique when water and ethanol were used as solvents (Lasta et al. 2019).

4.2.3 Subcritical Water

The subcritical water extraction technique is also seeking the attention of the scientific community for the extraction of phenolic compounds from food waste. Water as a solvent is used at a temperature of about 100–374°C with 10–60 bar pressure (Herrero et al. 2006). The subcritical water extraction technique is a promising eco-friendly technique for the extraction of bioactive compounds from fruits and vegetables (Zakaria and Kamal 2016). Factors that directly affect the liquid state of water are temperature, solubility, and dielectric constant. Compounds with antioxidant properties are extracted from vegetable waste with higher yield through this method. Various compounds like caffeic acid, coumaric acid, gallic acid, and chlorogenic acid are mainly extracted with this method. This environment-friendly technique is essentially used for nonpolar phytochemicals resulting in higher yield with lesser time consumption (Plaza et al. 2010). Rangsriwong et al. (2009) reported the extraction of polyphenols from *Terminalia chebula Retz* fruits, where increased gallic and ellagic acid were observed at water temperature about 180°C, and the highest amount of corilagin obtained was at 120°C. Singh and Saldaña (2011) have extracted phenolic acids like gallic acid, caffeic acid, proto-catechin syringic, ferulic acid, p-hydroxyl benzoic acid, and coumaric acid from the potato peels using this method. The highest yield of 81.8 mg/100 g of phenolic compounds was recovered at a temperature of 180°C with a holding time of 30 min from potato peels, where chlorogenic and gallic acid were the main products obtained as 14.6 mg/100 g and 29.6 mg/100 g, respectively. Mayanga-Torres et al. (2017) utilized coffee waste in two different forms, that is, cake and powder, through semicontinuous flow water in subcritical form. They obtained the highest amount of phenolic compounds as 26.6 mg GAE (gallic acid equivalent)/g with powder, at 220°C with 22.5 MPa pressure. Zhang et al. (2020) extensively reviewed the extraction of bioactive compounds using subcritical water and further utilization of the extracted compounds for value-added products.

4.2.4 Enzyme-Assisted Extraction

Enzymes have also been used for the extraction of bioactive compounds from vegetable and fruit waste. Specialized enzymes such as pectinase, β- gluconase, and cellulose have been used to extract compounds like cellulose, pectins, and hemicellulose from the plant cell wall (Moore et al. 2006; Singh et al. 2016). Enzymes like cellulase and pectinase were jointly used for lycopene extraction from tomato peel (Zuorro et al. 2011). Enzymes disrupt the cell wall structure to extract phenolic compounds under optimized conditions using alone or accompanied by other methods (Gardossi et al. 2010). Puri et al. (2012) reported the extraction of stevioside as a bioactive compound using *Stevia rebaudiana*, possessing health-promoting factors. Tannase enzyme is preferred over pectinase for enhancing the quality of black tea (Chandini et al. 2011). Cellulase, β-glucosidase, and pectinase are used to extract apegenin and luteolin from pigeon pea. Gallic acid extracted from agricultural waste with the help of this method is a good by-product to be used as a food additive (Curiel et al. 2010). Gurumallesh et al. (2019) screened, extracted, purified, and characterized protease enzymes from banana peels.

4.2.5 Ultrasound-Assisted Extraction

The ultrasound-assisted extraction technique is one of the most efficient and simple techniques compared to other traditional methods for the extraction of bioactive compounds from food waste. Ultrasound produces cavities into cellular matrices, which cause the penetration of the solvent into the cellular material of the vegetables and fruit waste, thereby facilitating the release of bioactive compounds. Ultrasound frequency of 20–2000 kHz is usually used to extract bioactive compounds from vegetable and fruit waste. The efficiency of this method greatly depends upon sonication time and frequency. High-intensity ultrasound creates voids or cavities, which also absorb and press out sound during expansion and compression. This whole process is based on the phenomenon known as acoustic cavitation (Esclapez et al. 2011). A study by Rostagno et al. (2003) reveals the extraction of four different isoflavone derivatives when different variants of sonication time and solvents were used. Variable isoflavones are diadzen, malonyl genistin, glycitin, and genistin from soybean waste. Piñeiro et al. (2004) extracted stilbenes rapidly from grape canes at optimum conditions like temperature, time, and 60% ethanol at 75°C for 10 mins. Kulkarni and Rathod (2016) used microwave-assisted extraction to extract mangiferin from leaves of *Mangifera indica,* and water was taken as a solvent with a maximum production of 55 mg/g at a power of 272 W for 5 min. Chen et al. (2015) also utilized this technique to extract unstable phenolic compounds under specialized conditions to enhance yield. The tannin yield was increased to around 160% when extracted from Avaram shell with sonication at 100W, and the yield of polysaccharides becomes 3.13% more from mulberry fruit waste. However, in another study, high-power ultrasound pretreatment was used successfully to recover fragments with enhanced antioxidant activity and pectins from rejected carrot waste (*Daucus carota* L.) (Idrovo Encalada et al. 2019). Ultrasound-assisted extraction was also used to recover heat-sensitive compounds like carotenoids from tomato peels (Szabo et al. 2021).

4.2.6 Pulsed Electric Field Extraction

The pulsed electric field extraction method is a nonthermal extraction process in which separation is done based on electric charge when cells are entered into electric field having dipole moment leading to separation of compounds having different charges through pores formed into the membrane (Bryant and Wolfe 1987). Electric current, energy strength, pulse, and temperature are the factors on which the separation of molecules depends (Heinz et al. 2003). A bit rise in temperature can lower the damage of thermolabile compounds at an electric field of 1000V/c for 10^{-4} to 10^{-2} sec (Fincan and Dejmek 2002). This method was proved better than other mechanical methods for the extraction of phenolic compounds. This treatment also increases the yield of extracted compounds like phytosterols, isoflavonoids, anthocyanins, and polyphenols (Corrales et al. 2008). Phenolic compounds like anthocyanins and phenolics were also extracted successfully from Merlot skin (Delsart et al. 2012). This method is preferred over maceration because it increases stability and reduces the time of extraction. Luengo et al. (2013) reported that the yield of phenolic compounds from orange peels increased by 159% when the pulsed electric power of 7kV/cm was used. Siddeeg et al. (2019) demonstrated the effect of pulsed electric field on the recovery of bioactive compounds and phenolic compounds from date palm fruit extract with 10 Hz frequency for 100 μs, with 30 pulses, and 1, 2, 3 Kv/cm electric field. It is further suggested that a pulsed electric field is a more appropriate technique to fasten the extraction process for commercial purposes. In another study on extraction of betalains as bioactive compounds from beetroot, the pulsed electric field at different electric field strengths of 4.38 and 6.25 kV/cm, with 10–30 pulse numbers, and 0–12.5 kJ/kg of energy input was used to enhance the efficiency of the extraction process (Nowacka et al. 2019).

4.2.7 Microwave-Assisted Extraction

Microwave-assisted extraction is associated with the electromagnetic radiations used at a frequency of 300 MHz–300 GHz and ranging similar to 600–700 Watts energy, resulting in the material's hydrogen bond breakage. Energy conversion occurs when microwave frequency of energy is absorbed and converted to thermal energy (Zhang et al. 2011). The main advantage of using the microwave-assisted method over the conventional method is its high yield. A maximum of 82.74% flavonoids was extracted from the plant "*Terminalia bellerica,*" around 19% more than traditional methods (Krishnan and Rajan 2016). Another example of the technique mentioned above is the extraction of hesperidine from citrus fruits skin with a yield of around 86.8%. Modernity in science attracts toward this method due to cost efficiency both in processing and setup. The production of bioactive compounds is also high with simple processing conditions in this approach. This method also works on the principle of poring membranes of biological organelles by changing their temperature, thereby causing evaporation of inner cellular moisture, which results in the entry of solvents followed by extraction of phenolic compounds of interest (Routray and Orsat 2011). The physical environment inside the cell and several characteristics of solvents like power, frequency, type, and concentration matter greatly for this method (Mandal et al. 2007), and polar solvents are preferred over nonpolar solvents due to difference in absorption of microwave frequency (Wang and Weller 2006). The method mentioned above proved its acceptance in yielding more with less time consumption and beneficial due to its eco-friendly approach. The extraction of compounds including catechin, mangiferin, phenolic compounds, polyphenols, and saponins is preferred by this method. This is also a method of choice to extract phenolic compounds, carotenoids, terpenoids, alkaloids, and saponins possessing antioxidant properties (Moreira et al. 2012). Many polyphenol and bioactive compounds were also recovered from vine pruning waste using conventional heating and microwave-assisted techniques (Jesus et al. 2019).

5 Valorization of Extracted Phenolic and Bioactive Compounds into Functional Value-Added Products

Vegetable and fruit waste is among the highest wasted commodity, with nearly half of the fresh produce wasted annually (FAO 2011). Fresh vegetable and fruit produce represent inedible components that are to be discarded like seeds and outer layers. The nonedible portion is variable for particular vegetable and fruit commodities like bananas (nearly 35%), pineapples (47%), citrus (25–35%), watermelon (48%), and apples (12%). Similarly, the case of vegetables like cauliflower and broccoli (43%), garlic (22%), carrots and turnips (20%), etc. constitutes the nonedible portions (De Laurentiis et al. 2018). The remains of vegetables and fruits mainly consist of pomace, seeds, skins, and peels, which are enriched with nutrients for the production of high value-added bioactive compounds like flavonoids, dietary fibers, phytochemicals, polysaccharides, proteins, and flavor compounds (Kumar et al. 2017; Kowalska et al. 2017; Sagar et al. 2018; Ran et al. 2019).

5.1 Bioactive Compounds from Vegetable Waste and Their Possible Utilization

Vegetables are an important commodity of our daily diet enriched with phytonutrients producing nutraceutical effects on our health system. Vegetable waste is generated mainly in the producing areas like farms, where fresh produce is wasted due to improper handling practices. It mainly consisted of leftover produce, stems, leaves, or fruits. Vegetable waste is generated domestically and through industrial methods where vegetables are processed to produce commercial products like potatoes to manufacture potato chips or other for canned vegetables. However, these practices generate enormous amounts of waste, which can be valorized into some value-added products to prevent such wastage. However, recent trends of consuming ready-to-eat vegetables, precooked meat, canned veggies, and salads have piled up the industrial vegetable wastes. These vegetable wastes are enriched with phenolic and bioactive compounds, which can be further exploited righteously into sustainable, functional products of high value. Therefore, some of the prevalent vegetable commodities like phenolic and bioactive compounds extracted from vegetable waste and their conversion into functional products have been addressed in the present section of the chapter.

Cauliflower (*Brassica oleracea* var. Botrytis), belonging to the Brassicaceae family, generates around 35% of waste in the form of stems and leaves (Ospina Machado and Villamizar 2004). Amofa-Diatuo et al. (2017) reported the development of a new beverage based on apple juice rich in isothiocyanates obtained from cauliflower waste using ultrasound-assisted extraction at different amplitudes ranging from 20 to 100% with extraction times ranging from 0 to 10 min at a frequency of 24 kHz. The highest recovered total phenolic compounds were equivalent to 105 mg GAE/L μM under optimized conditions (ultrasound-assisted extraction with 100% amplitude for 3 min) added to apple juice (10–40%). The obtained beverage was palatable without any color differences.

Carrot (*Daucus carota* L.) is a popular vegetable grown worldwide with different varieties depending on season variation. Carrots are considered a rich source of significant phytochemicals like phenolic compounds and carotenoids that can be extracted and further valorized into natural colorants for food and pharma sectors (Stahl and Sies 2005). However, carrot peels were exposed to supercritical CO_2 with ethanol as a solvent under optimized conditions (temperature 60°C, 350 bar pressure, and 16% of ethanol) to extract the carotenoids for industrial applications. As a result, the maximum recovery rate for carotenoid yield from carrot peels was 86% (De Andrade et al. 2018). Furthermore, Idrovo Encalada et al. (2019) reported pectin-enriched fractions from carrot waste that was further utilized for formulations for functional foods due to the antioxidant effect shown by α-tocopherol, lutein, and α- and β-carotenes.

Beetroot (*Beta vulgaris* L.) is a popular vegetable and a natural colorant used widely to produce sugar and ethanol. After processing, the residue of beetroot is discarded as fodder, which includes stems and leaves, which are a rich source of bioactive compounds. However, Lasta et al. (2019) exploited the waste from beetroots. As a result, they recorded the highest total phenolic content of 99 mg GAE/g and 98 mg GAE/g for leaves and stems, respectively, through supercritical fluid extraction technique using ethanol and water as the solvent and only ethanol as co-solvents. Furthermore, it was also suggested that the extracted bioactive compounds have a high potential for the food and pharma sectors.

Potato (*Solanum tuberosum* L.) is a popular vegetable gown in abundance after staple crops. Potato is widely used at an industrial scale and domestically to manufacture potato-based snacks, most loved by consumers. However, potato processing generates a massive amount of waste in the form of peels, which have a high content of bioactive compounds compared to the flesh, mainly focusing on phenolic acids and glycoalkaloids (Friedman et al. 2017). Phenolic acids present in potato peels exhibit antioxidant and antibacterial activities, which also help reduce the risk of cardiovascular diseases and diabetes. These also have antitumor properties, and potato starch has proven to be a rich source of pectin. Samotyja (2019) explored the potato peel extracts from two different varieties of potatoes like Jazzy and Gala. Extracts using 96% ethanol showed the highest total phenolics of 28 mg/g of dry weight. These extracts helped in inhibiting the oxidation of rapeseed oil and also delayed volatile formation in sunflower oil.

Moreover, the phenolic compounds present in potato peel extract have proven to extend the shelf life of food. Martinez-Fernandez et al. (2020) demonstrated a Sequential Hydrothermal Extraction (SeqHTE) process for recovering value-added products from potato peels. The recovered polyphenol content was 33 mg/g dry peel, and these extracts exhibited substantial antioxidant activities, ranging from 40 to 92%.

Broccoli (*Brassica oleracea* var. *italica*) is a popular salad vegetable well known for its antioxidant properties. However, despite its health-promoting values, 25% of the total produce is wasted due to improper handling. Broccoli waste is rich in glucosinolates (0.2–2% dry weight sample), mainly glucoraphanin (32–64%) with total phenolic content less than 0.02% dry weight sample (Thomas et al. 2018). Formica-Oliveira et al. (2017) demonstrated the effect of different ranges of radiation treatments of UV-B (5, 10, and 15 kJ m^{-2}) single or mixed with UV-C (9 kJ m^{-2}) to augment the extraction of bioactive compounds from broccoli waste, including leaves and stalks. Leaves showed 2.5% higher glucoraphanin and 14.5% more glucobrassicin yield than floral parts and the same total phenolic and antioxidant effect. However, further treatment of leaves and stems of broccoli waste with UV enhanced initial total phenolic content and antioxidant effect of leaves up to 31–97% and 20–120%, respectively, whereas, for stalks, total phenolic content and the antioxidant effect were raised to 30–75% and 170–420%, respectively. When the combined effect of UV-B10 and UV-C was used, total phenolic content was increased to 110% in leaves, while in stalks, UV-B10 and combinatorial effect of UV-B10 and UV-C tempted maximum total phenolic content after 48 h. In addition, a 34% increase in glucobrassicin was observed among leaves when UV-B10 combined with UV C was used. In contrast, utmost levels of glucoraphanin of 131 mg/kg and 117 mg/kg^{-} were observed in florets when UV-B15 and a combination of UV-B15 and UV-C were used, respectively. Hence, from the studies mentioned above, it has been determined that UV-B or UV-C treatment can help valorize discarded broccoli waste into value-added products.

Tomato is among the most popular vegetables consumed almost in every part of the world due to its high nutritional content, enriched with lycopene, phenolic compounds, vitamins, and organic acids (Giovanelli and Paradiso 2002). Tomato is consumed fresh and in the form of processed products such as purees, juice, ketchup, salad dressings, and many other restaurant servings (Kaur et al. 2008). But most of the tomato products containing valuable compounds are going to waste due to their perishable nature and lack of processing facilities (Sooch and Mann 2021). Industrial tomato processing also generates around 6–32% of total products as underexploited waste in peels and seeds known as tomato pomace. Several scientific studies reveal valuable bioactive compounds present in the tomato industrially processed leftover, such as phenolic compounds, carotenoids, dietary fibers, and polyunsaturated fatty acids (Grassino et al. 2020). Szabo et al. (2021) demonstrated that oil could also be produced from tomato seed waste, which can be used for consumption or in combination with functional foods and is rich in bioactive compound having health-promoting factors. Lu et al. (2019) extensively reviewed the utilization of tomato pomace for fodder and additives in fine powders of tomato seed pomace into meat, flour-based foodstuffs, and edible pastes as flavor enhancers and to increase the nutritional yield of functional foods. Hence, utilizing tomato pomace in functional foods is sustainable for developing value-added products based on tomato waste. Szabo et al. (2020) reported the preparation of intelligent and active food packaging films from polyvinyl alcohol, itaconic acid, and chitosan, where tomato processing waste (having total phenolic compounds of 0.21 mg gallic acid/100 mL film mixture and carotenoids) was incorporated into the film mixtures to impart antioxidant and antimicrobial effect. The prepared active food packaging films with tomato pomace showed substantial antimicrobial effects against *Staphylococcus aureus* and *Pseudomonas aeruginosa.*

5.2 Bioactive Compounds from Fruit Waste and Their Possible Utilization

Many bioactive compounds from fruits were extracted and used in many applications in various products to treat various health ailments. Banana (*Musa* genus) fruit is one of the most consumed fruits due to its availability at low cost and health-promoting benefits. Banana fruit processing generates large amounts of fruit wastes such as peels, stalks, leaves, pseudo-stems, rhizomes, etc. Banana peels are rich in dietary fiber, containing insoluble dietary fiber such as lignin, hemicellulose, cellulose, and pectin, a soluble dietary fiber. The toxins present in banana peels include hydrogen and oxalates, constituting around 1.3 mg/g and 0.5 mg/g, respectively (Benjamin et al. 2009). Pectin is another very important component, and it can also be extracted from banana peels. The unwanted fragments are separated during banana processing operations and can be further used to extract bioactive components (Mathew and Negi 2017; Vu et al. 2018). Gurumallesh et al. (2019) screened, extracted, purified, and characterized protease enzymes from banana peels. Twelve various species of banana peels were screened for protease enzyme activity. The maximum activity of the extracted enzyme was found to be 230.4 CDU (Collagen Digestion Units)/mg from Nendran banana under optimized conditions of temperature 30°C and pH 7. The obtained enzyme was tested for its cytotoxicity, apoptosis, and anticancer properties. It was found to be highly significant and efficient in health promotion and breaking down of peptide bonds.

Mango peels as a by-product from juice processing industries or domestic consumption have been regarded as waste as the peels subsidize about 8–23% of the major fruit. Mango peels are rich in phenolics and flavonoids as compared to papaya and pineapple peels (Ayala-Zavala and González-Aguilar 2011). Mango peels possess higher bioactive compounds than other plant parts (Sultana et al. 2012). Ajila et al. (2007) reported the functional and antioxidant characteristics of mango peels due to the presence of higher amounts of carotenoids, phytochemicals, polyphenols, vitamin C, enzymes, and vitamin E. Adilah et al. (2018) exploited the antioxidant properties of mango peels extract and incorporated it into active fish gelatin packaging films which produced a thick, dense, and intact structured film with outstanding free radical scavenging property at a concentration of 1–5% of mango peel extract. Ballesteros-Vivas et al. (2019) demonstrated a novel valorization approach for mango seed kernels. A versatile green pressurized-liquid extraction strategy was employed along with a comprehensive high-resolution mass spectrometry-based phytochemical classification technique for bioactive evaluation of fractions with high antioxidant effects and antiproliferative property against cancerous human colon cells. A comprehensive gas chromatography (GC) and liquid chromatography quadrupole time-of-flight mass spectrometry (LC-Q-TOFMS) profiling yielded complete classification of the phenols and lipid fractions acquired under optimal conditions with 100% ethyl alcohol at 150°C, indicating the high yield of stearic and oleic acids along with other bioactive phenolic acids, flavonoids, xanthones, gallotannins, and derivatives of gallate. The mango seed kernel extract showed a higher antiproliferative effect against human colon adenocarcinoma cell line HT-29 with valuable potential to scale up a therapeutic commercial value-added product.

Apple (*Malus* spp.) has been considered a popular fruit due to its deliciousness and special therapeutic effects. Its health-promoting benefits prevent certain heal ailments related to pulmonary disorders, cardiovascular diseases, obesity, cancer, etc. It is grown, harvested, and exported to many countries worldwide, where a substantial amount of apple is processed to obtain juice or cider. The processing of apples for juice production generates piles of waste known as apple pomace, which constitutes around 25% of the fresh fruit produced. Apple pomace comprises peels, core, stems, and seeds (Waldbauer et al. 2017). The high sugar content of 48–62% on a dry weight basis and moisture content of 66–78% render the apple pomace vulnerable to perishing; thereby, its storage for longer durations is not economically viable (Joshi and Attri 2006). Apple pomace contains more phenolic compounds than fresh apple fruit (Krawitzky et al. 2014). This is a low-cost source of bioactive components like polyphenols, pectin dietary fiber, volatiles, and triterpenoids (Waldbauer et al. 2017). Many extensive studies have been conducted to identify phenolic compounds present in apple pomace, which were found to be anthocyanins, flavanols, flavones, flavanones, dihydrochalcones, and hydroxycinnamic acids (Ramirez-Ambrosi et al. 2013). The phenolic content in fresh apple pomace is caffeic acid, chlorogenic acid, catechin, quercetin glycosides, rutin, and phlorizin, which are found to be the most protruding polyphenol after freeze-drying of apple pomace (Ćetković et al. 2008). Di-hydrochalcones are the major polyphenols found in stems and apple seeds, with chlorogenic acid and flavonol glycosides present in apple flesh (Górnaś et al. 2015). The phenolic compounds present in apple pomace possess antioxidant (Kusumawati and Indrayanto 2013), antimicrobial (Wu et al. 2013), antiproliferative, anti-inflammatory, cardioprotective, and antitumor characteristics. They effectively inhibit reactive oxygen species and other microbial infections caused by bacteria, fungi, and viruses, thereby making them attractive to be used in dermal products (Zhang et al. 2016; Fialova et al. 2017). Działo et al. (2016) reported that in vitro and in vivo studies of phenolic compounds from apple pomace works well against skin damages like burns and injuries, antiaging, psoriasis, dermatitis, and tumors. Barreira et al. (2019) extensively reviewed the health-promoting benefits of phenolic and other bioactive compounds from apple pomace like dihydrochalcones, flavonoids, and hydroxycinnamic acids. Further, they suggested that these compounds are anti-inflammatory, antimicrobial, and antioxidant, which can be exploited in the food and pharmaceutical sectors to develop novel food or dermal products.

Avocado (*Persea americana*) is a tropical fruit mainly grown in Mexico and Central America and is gaining attention due to its fat-soluble phytochemicals. Avocado pulp consisted of 70% insoluble and 30% soluble fibers and enriched with proteins, polyphenols, phytoestrogens, tannins, pigments, and sugars like sucrose and 7-carbon carbohydrates (Cowan and Wolstenholme 2016). The avocado fruit consisted of dull or leathery peels, soft green flesh, and a prominent round, hard, and heavy seed. The avocado processing industry extracts essential oils, and the exhausted residues containing seeds and peels are discarded as waste, which accounts for about 21–30% of the fruit (López-Cobo et al. 2016). The residual portion of the avocado processing is rich in bioactive components, especially polyphenols and proanthocyanidins. Avocado waste consisted of phenolic compounds like caffeoylquinic acid, catechins, quercetin glycosides, coumaroylquinic acid, and procyanidin trimmers (López-Cobo et al. 2016). Avocado waste can act as a good source of antioxidants, antimicrobials, colorants, flavoring agents, and thickeners

(Ayala-Zavala and González-Aguilar 2011). Rotta et al. (2016) demonstrated the use of avocado waste polyphenols into beverages to impart an antioxidant effect. These can also be used to prevent meat oxidation (Utrera et al. 2012). Seed starch from avocado waste can be used to form food packaging films due to its biodegradation effect (Chel-Guerrero et al. 2016). Araújo et al. (2018) extensively reviewed the use of avocado polyphenols for nutritional and environmental perseverance. These possess many health benefits and dermatological uses due to their antimicrobial, antioxidant, and anticancer properties.

Barros et al. (2017) conducted a study on some Brazilian exotic fruit (achachairu, araçá-boi, and bacaba) residues to investigate the bioactive compounds and their antioxidant effects, which were evaluated by oxygen radical absorbance capacity (ORAC), FRAP, and ABTS (2,2'-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid) assays. The total phenolic compounds detected were carotenoids, flavonoids, and chlorophylls and were quantified using UHPLC-QqQ-MS/MS (Ultra high-performance liquid chromatography coupled with triple quadrupole mass spectrometry system). In addition, a number of compounds like *p*-coumaric acid, cinnamic acid, quercetin, and epicatechin were detected and quantified in the fruit wastes mentioned above. The highest antioxidant value detected for bacaba was 15,286 μmol TE/100g through ORAC and 16916 μmol TE (Trolox equivalent)/100 g through FRAP assay 1537.45 ± 73.35 mg GAE (gallic acid equivalents)/100 g as total phenolic content in its methanolic extract.

Cranberries, blueberries, bilberries, and lingonberries belonging to the genus *Vaccinium* have been cultivated widely worldwide for juice processing industries. Huge amounts of pomace as berries waste have been generated after pressing berries for juice, which is rich in polyphenols. The total anthocyanin content was determined for all the varieties mentioned above of *Vaccinium* genus through UPLC (Ultra-performance liquid chromatography) and LC-TOF/MS (Liquid chromatography-time-of-flight mass spectrometry) analysis. The total anthocyanin content in bilberries residues was 285 mg/g, which includes 84/g in bush blueberry residues, 44 mg/g in cranberry residues, 8 mg/g in American cranberry residue, and 28 mg/g in lingonberry residue (Klavins et al. 2018).

Date fruit (*Phoenix dactylifera* L.) seeds are an abundantly available source of bioactive compounds. Djaoudene et al. (2019) analyzed the phytochemical and antioxidant analysis of the date seeds from eight varieties. They found the highest total phenolic content of 476 mg GAE/g DW (dry weight) with total flavonoids 7 mg QE (quercetin equivalent)/g DW, flavonol 3.3 mg Q3GE (quercetin 3-glucoside equivalent)/g DW, anthocyanin 1.2 mg Q3GE/g DW, proanthocyanidin 85 mg CE (cyanidin equivalent)/g DW, and ascorbic acid was identified in the seeds of Tazoughart "TAG" variety.

Citron *(Citrus medica)* consists of many bioactive compounds like citral as iso-limonene, phenolics, vitamin C, flavonoids, linalool, decanal, nonanal, and pectin present in all parts of the plant rendering many health benefits. As mentioned above, these bioactive components present in the fruit can act as anticancer, antimicrobials, antioxidants, cardio-protectors, anti-hypersensitivity, diuretics, anthelmintic, and painkiller and help protect against diabetes (Chhikara et al. 2018).

Furthermore, Gómez-Mejía et al. (2019) reported flavanone hesperidin in the range of 280–673 mg/g as the highest polyphenol content in the citrus peels. They suggested that these polyphenols can lead to the scale-up of high value-added products with good therapeutic value. However, from the description mentioned above about the functional products from fruit waste, it has been remarked that the fruit waste consisted of many phenolic compounds and other bioactive compounds, which can be further utilized in the production of industrially important food or pharmaceutical products of higher value.

A plethora of studies based on the utilization of waste from diverse vegetable and fruit residues further indicates that this waste has a lot of potentials to produce many functional value-added products, which is still underexplored. These processes need practical implications to be scaled up from laboratories to industries to develop actual high-end products based on the valorization of food residues in biorefineries.

6 Recent Trends in Patenting of Phenolic and Bioactive Compounds from Vegetable and Fruit Wastes

Globally, the utilization of phenolic and bioactive compounds from vegetable and fruit waste into various functional value-added products has been achieved by many researchers. Several patents about the same have been granted. Phenolic and bioactive compounds extracted from industrial vegetable and fruit residues have abundant applications in functional foods, food packaging, and the pharma sector.

Puupponen-Pimiä et al. (2021)) have been granted a patent on transforming waste residues from berry fruit fragments, particularly seeds having bioactive compounds, thereby subjecting the seed fragments and seed coat to sanding to obtain sanded seeds. Similarly, Conde et al. (2020) invented a method to extract hydroxycinnamic acids and characterize their formulations from vegetable residues from vegetable-based food products. Green (2015) described an invention related to methodology producing a crystalline powdered extract of polymethoxylated flavones isolated from citrus (Ortanique) peels for industrial utilization. Norddahl and Parjikolaei (2020) invented methods to extract natural phenolic acids, cinnamic acid, ferulic acid, caffeic acid, cichoric acid, chlorogenic acid, sinapic acid, benzoic acid, gallic acid, etc. and natural antioxidant-rich pigments consisting of polyphenols, tannic acid, anthocyanin, phenol, ellagitannin, catechin, flavonoid, and flavonol from the pomace of selected fruits (blackberries, apple, red currants, cherries, elderberry, raspberry, strawberry, black chokeberry cowberry, bilberry, etc.). A brief account of patents related to bioactive and phenolic compounds from fruit and vegetable residues for industrial value-added products has been enlisted in Table 4.2. Edwards (2000) has developed an innovative method for the extraction of bioactive components from banana peel. A composition resulting from extracting carotenoids from fruit and vegetable processing waste was patented by Allen and Rusnack (2009). Rupasinghe and Robertson (2015) described an invention related to the extraction of

Table 4.2 List of patents on phenolic and bioactive compounds derived from vegetable and fruit residues and their possible utilization

Sr. no.	Patent/application no.	Patent title	Year of Filling/ grant	References
1.	US4126709A	Method for extracting carotenoid pigments from citrus oils	1978	Johnson et al. (1978)
2.	US 4,497,838	Process for the production of useful products from orange peel	1985	Bonnell (1985)
3.	EP0096481A1	Extraction and intensification of anthocyanins from grape pomace and other material	1987	Shrikhande (1987)
4.	US 5,792,461	Citrus peel extract as 3-hydroxy-3-methylglutaryl CoA(HMG-CoA) reductase inhibitor	1998	Bok et al. (1998)
5.	US 6,013,260	Banana peel extract composition and method for extraction	2000	Edwards (2000)
6.	US 6,183,806	Method of making citrus fruit peel extracts and flour	2001	Ficca et al. (2001)
7.	US6391345B1	Cranberry seed oil, cranberry seed flour and a method for making	2002	Heeg and Lager (2002)
8.	US 20050147723 A1	Apple peel powder, methods of making and uses thereof	2005	Liu (2005)
9.	US 7,138,152	Process for extracting carotenoids from fruit and vegetable processing waste	2006	Allen and Rusnack (2006)
10.	US 7,201,928	Extracts of orange peel for prevention and treatment of cancer	2007	Huang et al. (2007)
11.	WO2008055894A1	Process for the extraction of lycopene	2008	Lavecchia and Zuorro (2008)
12.	US 7,527,820	Composition resulting from process for extracting carotenoids from fruit and vegetable processing waste	2009	Allen and Rusnack (2009)
13.	US 7,485,332	Citrus peel juice	2009	Chu et al. (2009)
14.	US 8.481,099 B2	Process for conversion of citrus peels into fiber, juice, naringin and oil	2013	Nafisii-Movaghar et al. (2013)
15.	US 20110250344 A1	Method for producing grape extract with high ORAC value, and grape extract so proudced	2011	Ying et al. (2011)
16.	US 20150125557 A1	Methods for the development of ortanique peel polymethoxylated flavones extract powder for commercial applications	2015	Green (2015)
17.	US 20150290274 A1	Phenolic compositions derived from apple skin and uses thereof	2015	Rupasinghe and Robertson (2015)

(continued)

Table 4.2 (continued)

Sr. no.	Patent/application no.	Patent title	Year of Filling/ grant	References
18.	US 9,017,755	Methods for making fruit or vegetable extract from by-products	2015	Luther et al. (2015)
19.	US 9,700,506	Antioxidant composition containing extract of processed *Chrysanthemum indicum* or *Citrus unshiu* peel	2017	Kim et al. (2017)
20.	US 9,981,204	System and process for extraction of products from apple peel	2018	Doucet (2018)
21.	US 20140314889 A1	Cardioprotective agents from kiwifruits	2014	Duttaroy (2014)
22.	US 20170223997 A1	Delivery of functional ingredients	2017	Wang et al. (2017)
23.	US 20170055526 A1	Antimicrobial antibacterial and spore germination inhibiting activity from an avocado extract enriched in bioactive compounds	2017	Hernandez-Brenes et al. (2017)
24.	US 10,844,226	Methods for obtaining natural colorants from plant based materials	2020	Norddahl and Parjikolaei (2020)
25.	US 10,736,862	Method for producing extracts containing hydroxycinnamic compounds from vegetable waste products	2020	Conde et al. (2020)
26.	US 11,044,935	Process for converting berry and fruit materials to antimicrobially active fractions	2021	Puupponen-Pimiä et al. (2021)
27.	US 10,967,020	Method of synthesizing custard apple peel nanoparticles	2021	Yehia et al. (2021)
28.	US 10,946,053	Composition containing mixed extract of mulberry and Poria cocos bark for preventing, improving or treating neuro-degenerative disorders	2021	Choi et al. (2021)

phenolic compounds particularly rich in flavonoid from apple skins, thereby producing antioxidant and anti-inflammatory effects in neurological disorders. Hence, from the details mentioned above about diverse inventions related to the utilization of vegetable and fruit leftover, it can be appraised that researchers are actively pursuing to convert this waste into functional value additives to exploit these natural phytochemicals and bioactive compounds present in vegetable and fruit waste discarded by the commercial sector.

7 Conclusions and Future Perspectives

Vegetable and fruit processing industries generate an unprecedented amount of waste that piles up into the environment and causes many pollution problems. Residuals of vegetable and fruit waste are generated through industrial practices and domestic garbage in the form of cores, peels, seeds, flesh, kernels, and deteriorated or unconsumed food servings in restaurants. The waste generated from an endless list of vegetables like broccoli, tomato, potato, cauliflower, beetroot, carrot, etc. and fruit commodities like pomace from apples, banana, berries, avocado peels, and seeds, citrus peels, mango peels, and seeds possesses a diversity of nutrients, bioactive compounds, phenolic compounds, vitamins, and fibers, which are dumped as waste without any utilization. Numerous bioactive and phenolic compounds with antioxidant, antimicrobial, and therapeutic properties can be extracted through various innovative waste valorization strategies. Several researchers have developed many advanced extraction processes and functional products based on these bioactive and phenolic compounds from food waste. However, despite the availability of many research reports and patents based on utilization of these vegetables and fruit residues showing advantages in curing of innumerable health ailments related to cardiovascular diseases, respiratory syndromes, neurodegenerative disorders, inflammation, and even anticancer potential, these have been lacking real-time implications to scale up from laboratories to industries. Therefore, in light of these residuals' potential mentioned above for the development of functional value-added products, there is a need of the hour to frame some sustainable strategies for making this happen at a large scale. This can be possible with the effective collaboration of research laboratories and industries, where these high-end products can be flourished. In addition, the scientific community should focus on practical implications for the appropriate utilization of these compounds into functional value-added products at the industrial level.

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Part III
Mushrooms, Livestock Feeds and Other Bioproducts

Chapter 5
Utilization of Fruit and Vegetable Wastes for the Cultivation of Edible Mushrooms

Manpreet Kaur Mann and Balwinder Singh Sooch

Abstract Food industries generate a plethora of waste materials, generally in the form of lignocellulosic materials, which are piling up in nature and creating havoc in waste disposal. Fruits and vegetables have been the highest consumed commodities among all food categories, and their consumption generates diverse types of residuals in the form of waste. These fruit and vegetable wastes in the form of peels, seeds, pods, stems, stalks, core, husks, straw, etc. are mainly constituted of lignocellulosic materials. These lignocellulosic materials can be easily used as a substrate for mushroom cultivation instead of dumping in landfills because mushrooms possess lignocellulolytic enzymes that can break down complex lignocellulosic materials through the solid-state fermentation process. Moreover, mushrooms have diverse medicinal and health-promoting properties to combat Parkinson's disease, hypertension, Alzheimer's disease, etc. Mushrooms also possess antimicrobial, antitumor, antidiabetic, and immunity-boosting properties. Therefore, owing to the inexhaustible nutritional and therapeutic benefits of mushrooms, the current chapter emphasizes on the valorization of agro-waste materials, especially fruit and vegetable wastes, to produce edible mushroom varieties.

Keywords Fruit waste · Vegetable waste · Mushroom · Mushroom cultivation

1 Introduction

India is the world's second-largest vegetable producer and accounts for 14% of the total global vegetable production. Fruit and vegetable processing units, typically followed by residential trash, contribute to the most waste generation into the environment (Gowe 2015). More than 1.6 billion tonnes of food are abandoned or discarded each year globally, resulting in substantial economic losses (about 750 billion USD) and severe environmental damage (FAO 2013). Many fruits and

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vegetables like oranges, pineapples, peaches, apples, potatoes, carrots, green peas, onions, artichokes, and asparagus are used for juice or pulp extraction, jams preparation, and frozen pulp preparation that result in a substantial amount of waste generation (Rodríguez et al. 2006). Moreover, fruit and vegetable waste (FVWs) are more prone to spoiling than cereal trash due to their chemical constituents. When discarded without treatment, this massive amount of untreated FVWs leads to significant environmental issues as they decay in landfills and release harmful greenhouse gases (Venkat 2011; Vilariño et al. 2017). In addition, it leads to an unhealthy situation, which in turn spreads illnesses and causes a significant resource loss.

Moreover, fruit and vegetable losses or waste reflect a waste of food commodities and vital resources, including land, water, fertilizers, chemicals, energy, and labor. Although some trash is unavoidable, but the correct utilization of waste materials obtained from horticulture commodities can help build a sustainable development effort for mushroom production and other valued goods. Mushroom cultivation on FVWs has proven to be a promising strategy for waste valorization into functional edible products. Edible mushroom cultivation is a cost-effective and practical approach for utilizing FVWs that can combat food insecurity.

Mushrooms have been considered macro-fungi with eminent sporocarp that may be present underground or above the ground and prominent enough to be handpicked. More than 2500 species of mushrooms have been identified in nature, with only 25 known species acceptable for human consumption. Among them, only ten species are of industrial interest. Furthermost mushroom species grown worldwide are *Agaricus bisporus*, *Lentinus edodes*, *Pleurotus* spp., and *Flammulina velutipes* (Valverde et al. 2015). Mushroom cultivation has risen continuously, and China is the leader in overall world mushroom production.

Moreover, among the edible species of mushrooms, only few are commercially grown and marketed. However, consumption is anticipated to rise further in the following years, with annual sales rising from 34 to 60 billion dollars. China generated 87% of the 35 billion kg of grown edible mushrooms consumed in 2013, with the majority consumed in the nation. This helps to explain why the button mushroom (*A. bisporus*), the most popular edible fungus in the Western world, ranks only fourth among farmed mushrooms (Royse et al. 2017). *Lentinula* known as shiitake, *Pleurotus* known as oyster mushrooms, and *Auricularia* known as wood ear mushrooms make up the top three edible mushrooms most consumed worldwide. In developing countries such as India, where 19.8 million children under the age of six are malnourished, only 9.6% of children aged 6 months to 2 years receive an adequate diet. Therefore, growing large quantities of mushrooms on inexpensive and readily available FVW from domestic and industrial practices can aid the countries in combating malnutrition. In 2013, the mushroom market was worth 63 billion dollars (Royse et al. 2017), and the share of medicinal mushrooms, wild mushrooms, and farmed edible mushrooms were 38%, 8%, and 54%, respectively. Mushrooms are very low in calories (27–30 kcal per100 g), have a low-fat content (1–8% of dry weight mushrooms), and are easily digested carbohydrates (Mattila et al. 2002). Edible mushrooms have been considered as beneficial foods as they include 5–15% dry matter, have a well-balanced mineral and vitamin content, and are high in fiber and protein (less than 2% fresh weight) (Mattila et al. 2002).

Moreover, it was also found that their amino acid content seems to be better when compared to vegetables like potatoes and carrots. Therefore, mushrooms have also served as a great source to attain sustainability. Furthermore, mushroom farming has also proven to address the significant issues that modern society faces, such as food insecurity, malnutrition, and environmental deterioration, as mushrooms can be easily cultivated on agro-industrial wastes (Niazi and Ghafoor 2021). Hence, the present chapter emphasizes the practical approach for the utilization of various FVWs that can be further valorized for the cultivation of edible mushrooms to achieve sustainability.

2 Classification of Edible Mushrooms

Edible mushrooms have many health-promoting factors as they are enriched with good protein, minerals, vitamins, fiber, and carbohydrates with low-fat content (Kalač 2013; Valverde et al. 2015). Mushrooms consisted of 35–70% carbohydrates and 15–37% protein with less than 5% (Valverde et al. 2015). Edible mushrooms also possess several medicinal properties, which make them attractive for human consumption. In addition to it, these mushrooms also have antimicrobial, anticancer, antidiabetic, antihypertension, and antitumor properties (Cheung 2010; Kalač 2013; Valverde et al. 2015). Nowadays, many varieties of edible mushrooms have been commercially exploited throughout the world. The utmost viable edible mushrooms that are commercially used belong to *Auricularia*, *Agaricus*, *Flammulina*, *Agrocybe*, *Hericium, Lentinula*, *Lentinus*, *Ganoderma*, *Pleurotus*, *Tremella,* and *Volvariella.* Among these, the most cultivated genera of mushrooms worldwide are *Pleurotus* known as oyster mushroom, *Lentinula*, commonly known as shiitake, *Agaricus* known as button mushroom, and *Auricularia* known as wood ear mushroom (Ma et al. 2018). Edible mushroom varieties cultivated most widely can degrade lignocellulosic substances through their ability to produce lignocellulolytic enzymes. In addition, these degraded materials are further utilized for their growth. Thus, the waste generated from the fruit and vegetable processing industries is a rich source for the production of mushrooms, which contributes to the valorization of FVW into value-added products. A schematic overview of the FVW valorization for the cultivation of mushrooms has been presented in Fig. 5.1. Thus, mushroom cultivation is often associated with the recycling of vast amounts of agro-industrial waste that can be valorized into value-added products (Sadh et al. 2018).

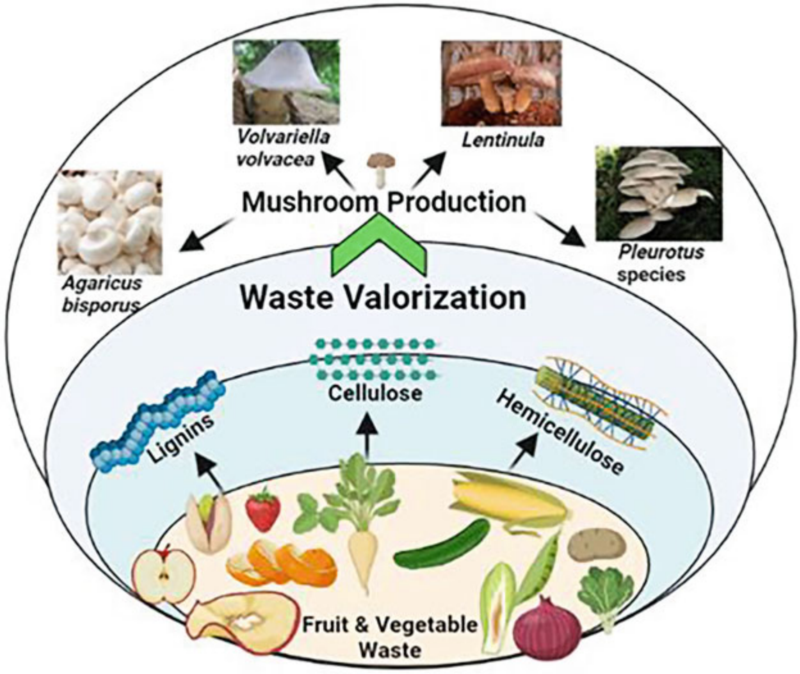

Fig. 5.1 A schematic outline of the fruit and vegetable waste conversion for mushroom production

3 Nutritional and Therapeutic Profile of Edible Mushrooms

Mushrooms have high nutritional value as they are enriched with protein, carbohydrates, fiber, vitamins, and minerals and are essentially low in fat content. Consuming mushrooms is considered a healthy practice for vegetarian adults as they provide all the necessary amino acids and account for the highest protein content than any other vegetable. In addition to high protein content, mushrooms contain several bioactive components that help to promote health (Li et al. 2021). Mushrooms also consist of four essential nutrients: glutathione, vitamin D, ergothioneine, and selenium, which act as antioxidants and relieve oxidative stress. Mushrooms also exhibit several therapeutic effects on health ailments related to hypertension, tumors, hypocholesterolemia, diabetics, immunostimulation, hypersensitivity, genotoxicity, and many more (Niazi and Ghafoor 2021). Moreover, mushroom cultivation is known to rise from 7 to 10 million metric tons during the last 10 years (Ho et al. 2020). Since pandemic prevailed, consumption of mushrooms has increased as some mushroom varieties like *Inonotus obliquus*, *Grifola frondosa,* and *L. edodes* have pronounced antiviral and anti-inflammatory effects against certain ailments caused by specific ailments SARS-CoV-2 (Shahzad and Anderson 2020).

Mushrooms are also enriched with many sugars, sugar alcohols, and sugar acids. It has also been found that mushrooms can suppress the growth of tumor cells; since then, various researchers have shown a massive interest in identifying the components of water-soluble polysaccharides derived from the fruiting bodies of mushrooms. Apart from this, a large part of the acidic polysaccharides designated as H51 is also found in mushrooms that claimed to have potent anticancer activity. Structurally, this component is made up of a skeleton of (1, 3)-linked glucose residues with galactose and mannose branches, as well as acidic sugars. Moreover, it was found that carbohydrate content in *Pleurotus* species ranges from 47% to 82% (as compared to 60% in *A. bisporus* on a dry weight basis). Fiber is regarded as an essential component of a well-balanced and nutritious diet (Rahi and Malik 2016). According to Anderson and Ward (1979), giving high-fiber meals to diabetic individuals lowers their daily insulin demand and stabilizes their blood glucose profile, possibly slowing glucose absorption. In addition, it was also found that *Pleurotus* species have the highest amount of fiber content ranging from 7.4% to 27.6% when compared with *A. bisporus* and *Volvariella volvacea* having fiber content of 10% and 4–20%, respectively.

Proteins are quantitatively diverse since they are built up of over 20 amino acids in variable quantities, out of which the human body can convert some. Still, nine essential amino acids are required to be supplemented from outside through nutrients. All nine essential amino acids must be present simultaneously and in the proper relative quantities for protein synthesis to occur. If one or more of these are in short supply, the use of all others in the cellular pool will be decreased proportionally. It has been found that animal-derived foods always provide a more balanced and higher quality protein than plant-based foods, which often lack some essential amino acids. Some cereal grains are deficient in essential amino acids like lysine, and legumes are also inadequate in methionine and tryptophan. However, such an issue can be resolved by consuming mushrooms filled with all the nine essential amino acids. Lysine is the most prevalent amino acid in all mushroom varieties, whereas tryptophan and methionine are the lowest. The edible mushrooms like *Agaricus* spp., *Lentinula* spp., *Pleurotus* spp., and *Volvariella* spp. contain a good amount of protein (1.8–3.63% by fresh weight) (Chang 1980). This percentage can be as high as 6%. However, an average of 3–4% appears to be more typical (Chang 1980). This indicates that edible mushrooms have roughly doubled the protein content of asparagus and cabbage and four times and 12 times the protein content of oranges and apples, respectively. These mushrooms contain about 19–35% protein content (by dry weight), while the protein content in rice, wheat, soybean, and milk is about 7%, 13%, 39%, and 25%, respectively. As a result, mushrooms rank behind from most of the animal products in terms of crude protein content but considerably above most other foods, including milk, an animal product. Sze Han et al. (2016) reported that *Pleurotus sajor-caju* contained protein, dietary fibers, sucrose, and fat values of 22 g, 57 g, 0.2 g, and 2 g (per 100 g), respectively. Boda et al. (2012) reported that *Pleurotus sajor-caju, Morchella esculenta, Pleurotus ostreatus, A. bisporus,* and *Boletus edulis* contained protein content of 1.60 g, 1.62 g, 1.68 g, 1.80 g, and 2.20 g (per 100 g), respectively, and denoted them as a commendable source of protein. In recent times, a newer category of specific ribonucleases commonly recognized as ribotoxin-like proteins has been revealed and extensively dispersed in various mushroom species (Citores et al. 2019; Fogarasi et al. 2020). Citores et al. (2019) identified Ageritin, a ribotoxin isolated from *Agrocybe aegerita,* and observed their diverse properties such as antiviral, antibacterial, cytotoxicity assay, nuclease, and endonuclease activities and urged that these can be exploited to develop plant's resistance against bacteria, fungi, and viruses through diverse transgenic techniques.

The fat content of various mushroom species ranges from 1% to 8%, with an average of 4% dry weight. Moreover, all types of lipid molecules are found to be present in the crude fat of mushrooms. Unsaturated fatty acids also play an important role in our diet. It has been found that unsaturated fatty acids account for at least 72% of total fatty acids in *A.bisporus* and *V. volvacea*. The unsaturated fatty acids are mainly attributable to linoleic acid, which constitutes 76% of total fatty acids in *L. edodes*, 70% in *V. volvacea*, and 69% in *A. bisporus*. Saturated fatty acids, which are abundant in animal fats, may be detrimental to our health. Still, a high proportion of unsaturated fatty acids and a high percentage of linoleic acid in these mushrooms can be a crucial element in its classification as healthy food (Rahi and Malik 2016). Furthermore, polyunsaturated fatty acids present in mushrooms have promisingly proved a reduction in serum cholesterol levels (Valverde et al. 2015).

Edible mushrooms are a rich source of thiamine (vitamin B1), riboflavin (vitamin B2), niacin, biotin, and ascorbic acid, among other vitamins such as vitamin C. Various researchers observed that thiamine levels vary from 0.35 to 4.80 mg in different varieties of mushrooms (*V. volvacea*, *A. bisporus*, *Pleurotus* spp., and *L. edodes)*. Likewise, niacin levels range from 46.0 to 108.7 mg in various mushrooms (*Pleurotus* spp., *L. edodes*, *A. bisporus*, *V. volvacea*). The riboflavin level of *A. bisporus* (5.0 mg) and *L. edodes* (4.9 mg) was greater than that of *V. volvacea* (1.63 to 2.98 mg). It was also reported that *A. bisporus* is enriched in folic acid, riboflavin, niacin, and thiamine but lacks vitamin C (Cağlarirmak 2009). Furlani and Godoy (2008) reported that mean values of vitamins B1 and B2 were 0.03 and 0.25 mg per 100 g, respectively, obtained from fresh samples of *A. bisporus.* Vitamin B2 content obtained from *A. bisporus*, *Pleurotus* spp., and *L. edodes* was greater than other vegetables. Mushrooms also have a good amount of mineral content as the developing mycelium absorbs the minerals in the substrate and transports them to the sporophores. It was found that potassium (K) is the most abundant mineral present in mushrooms like in higher plants, followed by phosphorus (P), sodium (Na), calcium (Ca), and magnesium (Mg), whereas copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), molybdenum (Mo), and cadmium (Cd) are the minor mineral elements that are present in mushrooms (Bano and Rajarathnam 1988). In addition, the concentrations of K, P, Na, Ca, and Mg are estimated to make up 56–70% of the total ash composition. However, potassium is present in abundance, accounting for approximately half of the total ash composition. In addition, most of the mushrooms have almost similar amounts of Na and Ca, except *L. edodes*, which has a very high level of Ca. Besides this, Cu levels were found more significant in all *Pleurotus* species than other edible mushrooms. The Cu, Ca, and lead levels in *Pleurotus* species ranged from 12.2–21.9, 0.3–0.5, and 1.5–3.2 μg/g, respectively (Rahi and Malik 2016). Notably, *A. bisporus*, the top-ranked mushroom species, is enriched with carbohydrates, minerals, vitamins, and amino acids and has potent anticancer, antifungal, antibacterial, anti-inflammatory, anti-obesity, and antioxidant properties (Usman et al. 2021).

4 FVWs as Substrate for Mushroom Cultivation

Agro-industrial waste is accumulating day by day with the increased population and consumption of fruits and vegetables. However, it piles up in the environment generating havoc on waste disposal. This kind of waste can be categorized into agricultural waste and industrial food processing waste. Waste generated through agricultural practices consisted of roots, leaves, stalks, stems, hulls, seed pods, and straw. However, industrial waste generally consisted of waste generated through processing fruits and vegetables, consisting of peels, pulp, seeds, husks, cores, bagasse, bran, pomace, etc. Mostly, the waste generated is incinerated or dumped into landfills, which is detrimental to the fauna and flora. Therefore, to nullify the detrimental effect of different types of FVWs disposed into the environment, there is a possibility for its conversion into value-added products like biofuels, bioactive compounds, functional foods, mushroom cultivation, and many more. Mann and Sooch (2020) extensively reviewed the valorization of food industrial waste to produce biofuels and bioactive compounds. Therefore, FVWs have a lot of potential for their utilization into valuable products. However, there is a pressing need to develop strategies to convert FVW into value-added products like mushroom production that can upsurge food security.

Agro-industrial waste comprises hemicelluloses, cellulose, and lignin that constitute lignocellulosic materials. Cellulose is considered as most abundant material, followed by hemicellulose and lignin (Kumla et al. 2020). Furthermore, the utmost palatable mushroom varieties are saprophytic in behavior and produce intense enzymes that decompose lignocellulosic materials. In turn, these degraded materials are used as nutrients for their evolution. Therefore, the agro-industrial waste is potent enough to cultivate mushrooms through various waste valorization strategies (Sadh et al. 2018).

Agricultural wastes and industrial FVWs both have been utilized as substrates for mushroom production. The substrate's carbon to nitrogen (C/N) ratio plays an important role in mushroom cultivation, and the waste generated from fruit and vegetable processing is generally low in nitrogen content. Therefore, the ratio mentioned above critically affects the growth of mycelium, the weight of the fruit, protein content, and yield of the mushrooms produced (Hoa et al. 2015; Grimm and Wösten 2018). Additionally, various supplements like salts of gypsum and limestone also trigger the mycelia growth and fruiting frame of the mushrooms (Grimm and Wösten 2018). The efficiency of the conversion of the substrate into mushrooms is termed as biological efficiency. This is a percentage proportion of fresh produce concerning the dry weight of the substrate (Moonmoon et al. 2011). The more the value of biological efficiency, the more is the possibility of utilization of substrates for mushroom production. The biological efficiency value should be greater than 50% (Kumla et al. 2020). Several researchers have demonstrated that mushrooms produced through the valorization of industrial food waste with appetizing proteins are suitable for human intake (Grimm and Wösten 2018; Sadh et al. 2018).

A plethora of studies have also been performed for mushroom farming using different FVW materials like banana leaves, peapods, cauliflower leaves, radish leaves, carrot, onion, cucumber, and potato peels in combination with agricultural waste like sawdust, bagasse, straw from wheat, barley, rice, oat, corn, stalks from soya, and sunflower. It has been concluded in most of these studies that there is a nutrient enrichment and increase of yield with the use of FVW materials as substrate in combination with agro-waste materials. Some fruits and vegetable waste materials used to cultivate a variety of mushrooms are listed in Table 5.1**.**

Some *Pleurotus* species were grown on cauliflower leaves, peapod shells, soybean husk, rice straw, and brassica straw. Some combinations of these materials with paddy straw were also tested for the cultivation of mushrooms. The biological efficiency of 94.3% and 91% was achieved for *Pleurotus citrinopileatus* when grown on peapod shell (70%) and cauliflower leaves (70%), respectively, in combination with paddy straw (30%), but mushrooms failed to grow in the absence of paddy straw (Shevale and Deshmukh 2016).

Koutrotsios et al. (2018) demonstrated the cultivation of some *Pleurotus* varieties on grape marc, olive mill waste, and wheat straw (control), and it was observed that grape marc-based substrate is the best material for *Pleurotus eryngii* and *P. nebrodensis*, but the production of *P.eryngii* was boosted in olive mill waste substrate. It was also recorded that grape marc and olive mill waste prompted larger mushroom fruiting bodies.

Banana pseudostems, paddy straw, and sorghum stalks were utilized to cultivate edible mushrooms such as *Lentinus connotus* and *Pleurotus eous* through the solid-state fermentation process. The maximum biological efficiency was 55–65% for paddy straw, 45% for sorghum stems, and 33% for banana pseudostems. Therefore, the study suggests bioconversion of lignocellulosic materials from agro-waste exhibited a promising approach for waste valorization and their conversion into scrumptious human foodstuff (Rani et al. 2008).

The vegetable waste materials in the form of peels of carrot, radish, potato, cucumber, and onion in combination with agro-waste like paddy straw, rice husk, wood shaving, and sugarcane bagasse were used as a substrate for the production of *P. ostreatus*. The absence of mycelium spread and fructification was observed with the use of only vegetable waste. However, the use of combination of vegetable waste and paddy straw in the ratio of 1:1 showed significant growth of mycelium. Thus, it was concluded in this study that vegetable waste can be a potent substrate for the cultivation of mushrooms (Shashitha et al. 2016).

Some chemosynthetic media and vegetable media in static culture were used to cultivate six wild edible mushrooms (*Russula lepida, R. brevipes, R. nigricans, Pleurotus sajor-caju, Lentinus tuberregium, and Calocybe indica*). The vegetable peel-based media such as drumstick peel medium, potato peel medium, carrot peel medium, bottle gourd peel medium, litchi peel medium, papaya peel medium,

Table 5.1 A list of fruit and vegetable waste materials used for cultivation of mushrooms

S. No.	Fruit and vegetable waste	Mushroom type	References
1.	Banana leaves	*Volvariella volvacea*	Garuba et al. (2017)
		Pleurotus ostreatus	Hoa et al. (2015)
		Volvariella volvacea	Belewu and Belewu (2005)
		Pleurotus florida	Tirkey et al. (2017)
2.	Banana stalks and Bahiagrass	*Pleurotus sajor-caju*	Siqueira et al. (2011)
3.	Cauliflower leaves, peapod shell in combination with rice straw	*Pleurotus ostreatus*	Shevale and Deshmukh (2016)
4.	Peels of carrot, radish, potato, cucumber and onion in combination with agro-waste like paddy straw, rice husk, wood shaving, and sugar-cane bagasse	*Pleurotus ostreatus*	Shashitha et al. (2016)
5.	Vegetable peel-based media (drum-stick peel medium, potato peel medium, carrot peel medium, bottle gourd peel medium, litchi peel medium, papaya peel medium, pointed gourd peel medium, chopped grass medium, little gourd peel medium, pumpkin peel medium, and rich gourd peel medium)	*Russula lepida, R. brevipes, R. nigricans, Pleurotus sajor-caju, Lentinus tuberregium, and Calocybe indica*	Behera and Gupta (2015)
6.	Vegetable waste (carrot, onion, rad-ish, cucumber, and potato peels) in combination with paddy straw	*Pleurotus ostreatus*	Komal et al. (2016)
7.	Pea pod shell, cauliflower leaves, radish leaves, and brassica straw in combination with paddy straw	*Pleurotus ostreatus*	Singh and Singh (2014)
8.	Pequi (*Caryocar brasiliense*) and guavira (*Campomanesia pubescens*)	*Pleurotus sajor-caju*	Silva et al. (2013)
9.	Winery and apple wastes	*Ganoderma lucidum, Lentinula edodes, Pleurotus ostreatus*	Petre and Petre (2008) and Petre (2013)
10.	Winery waste	*Ganoderma lucidum, Lentinula edodes*	Petre and Teodorescu (2010)
11.	Pomegranate peel and paddy straw in the ratio of 3:1	*Pleurotus florida*	Lalithadevy and Many (2014a, b)
12.	Grape pomace	*Pleurotus ostreatus*	Mhlongo et al. (2021)
13.	Apple pomace and wheat straw	*Pleurotus ostreatus*	Pathania et al. (2017)

pointed gourd peel medium, chopped grass medium, little gourd peel medium, pumpkin peel medium, and rich gourd peel medium were used as a substrate for the cultivation of mushrooms. It was found that papaya peel, drumstick peel, carrot peel, and bottle gourd peel medium are suitable substrates for growth augmentation in mushroom varieties like *Russula, Lentinus,* and *Pleurotus* sp. (Behera and Gupta 2015).

The nutrition enrichment in mushrooms (*P. ostreatus*) was explored using vegetable waste comprising of carrot, onion, radish, cucumber, and potato peels as substrate in combination with paddy straw. It was found that the combination gives a better yield in comparison to paddy straw alone. Furthermore, the mushrooms produced on vegetable waste in an assortment of paddy straw stored higher concentrations of proteins (20.98 mg/g), carbohydrates (56.57 mg/g), and phenols (344 μg/g) than those cultivated on paddy straw alone (Komal et al. 2016).

The substrate made with a combination of vegetable waste materials (peapod shell, cauliflower leaves, radish leaves, and brassica straw) and agricultural waste, that is, paddy straw, was used to cultivate *P. ostreatus*. The yield and biological efficiency of the mushrooms grown on a substrate prepared using paddy straw (70–80%) in various combinations with vegetable wastes (20%–30%) were more than mushrooms grown on paddy straw only. In this study, the mushrooms were not able to grow only on vegetable waste materials. There is a significant increase in protein and six essential amino acid contents (Leu, Ile, Val, Thr, Met, Phe) and decrease in total sugar and reducing sugar contents in the mushrooms produced on a substrate prepared with vegetable waste and paddy straw as compared to paddy straw alone (Singh and Singh 2014).

Similar observations were made when *Pleurotus sapidus* was grown on paddy straw combined with brassica straw, peapod shell, cauliflower leaves, and radish leaves. The maximum biological efficiency of 96.88% was noted with the use of substrate prepared with 30% peapods and 70% paddy straw, and this followed by the biological efficiency of 96.66% obtained with a substrate comprising of 30% radish leaves and 70% paddy straw (Singh and Singh 2012).

The fruit waste materials from Pequi (*Caryocar brasiliense*) and guavira (*Campomanesia pubescens*) were used as substrates for mushroom (*P. sajor-caju)* cultivation (Silva et al. 2013).

Banana leaves were also utilized as a substrate for the production of *V. volvacea* (Belewu and Belewu 2005). A substrate based on banana stalks and bahiagrass was used to cultivate *P. sajor-caju*. It was interpreted from the results that this substrate can afford the excellent growth of mushrooms without any other supplement (Siqueira et al. 2011).

In addition, the winery and apple wastes were also utilized as raw materials for mushroom compost preparation to obtain good yield with biological efficiency in the range of 20–28% for mushroom varieties, namely, *Ganoderma lucidum*, *L. edodes*, and *P. ostreatus* (Petre and Petre 2008; Petre 2013). Apple pomace and wheat straw-based substrates are used to cultivate mushrooms, and maximum biological efficiency of 8.8% was obtained when these were used in a 1:3 ratio, respectively. A significant increase in mushroom yield was also recorded with a combination of apple pomace and wheat straw compared to the experiment where only wheat straw was used as substrate (Pathania et al. 2017). The mushroom (*G. lucidum* and *L. edodes*) production of 1.5–2.8 kg per 10 kg of solid compost prepared from winery waste materials was obtained by Petre and Teodorescu (2010). Grape pomace was also utilized to cultivate oyster mushrooms, and reduced fiber content with increased crude protein content was recorded in the fruiting bodies (Mhlongo et al. 2021).

Tagkouli et al. (2020) revealed in a report on the evaluation of free fatty acid profile of *Pleurotus nebrodensis* cultivated on wheat straw alone and in a mixture with grape marc and waste residuals from the olive industry. Two other species of *Pleurotu,* namely, *P. eryngii* and *P. ostreatus*, were also cultivated, and 22 free fatty acids were determined, including ornithine, γ-aminobutyric acid (GABA), and essential amino acids. Free fatty acids ranged from 17 mg per g in *P. nebrodensis* to 130 mg/g in *P. ostreatus* (on a dry weight basis), including glutamine, leucine, alanine, valine, and serine outweighing.

Grape marc and olive mill wastes were used as substrates for producing edible mushroom variety *P. citrinopileatus*. Grape marc enhanced biological efficiency with small production cycles, whereas ergothioneine content was expressively higher in fruiting bodies grown on olive mill waste (Koutrotsios et al. 2021). Hence, various studies mentioned above on FVW utilization for mushroom production suggest that waste from fruit and vegetables contains an enormous nutritional content, thereby combating food insecurity and environmental disposal problems.

A detailed account of mushroom production along with the biological efficiency from FVWs has been summarized in Table 5.2**.**

The leftover mushroom substrate is considered as a waste residue, but it can be used as compost, animal fodder, biofuel production, enzyme production, food packaging implications, and a substrate for the production of other varieties of mushrooms. Furthermore, these practices can yield sustainable agricultural produce as the heat and the CO_2 generated from mushroom production can be utilized further to grow plants in greenhouses (Grimm and Wösten 2018).

The production of mushrooms is mainly done on lignocellulosic materials such as wood chips, sawdust, and straw, where the process transforms stumpy waste into superior foodstuff. Hence, it is important to enlist and compare the biological efficiency of mushroom production using only lignocellulosic substances like wheat straw, rice straw, sugarcane bagasse, olive oil waste, etc.

Faba bean hulls have been valorized for the cultivation of *P. ostreatus* (Jacq.). *P. Kumm* is known as oyster mushrooms and proved an appropriate substrate for mushroom cultivation with a biological efficiency of 109%. Post-harvest of mushrooms showed 48% of the initial dry weight of the substrate leftover that further displayed an elevation in protein content from 209 to 347 g per kg dry weight and a substantial upsurge in 14 among 16 amino acids. Anti-nutritional amalgams including vicine and convicine were found to be in low concentrations below the detection limits. Upon contrasting the mushroom spent substrate with regularly used feed for the pigs, spent from mushrooms indicated a higher potential for protein content in pig nutrition. However, the research mentioned above suggests the efficiency of the

Table 5.2 Valorization of fruit and vegetable waste for the production of mushrooms and their biological efficiency

S. No.	Fruit and vegetable waste valorized	Mushroom type	Moisture content (%)	Biological efficiency (%)	References
1.	Banana leaves	*Pleurotus florida*	81.20	91.50	Tirkey et al. (2017)
		Pleurotus pulmonarius	12.36	NA	Garuba et al. (2017)
		Pleurotus ostreatus	12.39	NA	
		Pleurotus ostreatus	NA	58.60	Hossain (2018)
2.	(a) Peapods (30%) and paddy straw (70%)	*Pleurotus citrinopileatus*	88	94.33	Shevale and Deshmukh (2016)
	(b) Peapods (20%) and paddy straw (80%)		86.86	90	
	(c) Paddy straw (100%)		89	90	
3.	(a) Cauliflower leaves (70%) and Paddy straw (30%)	*Pleurotus citrinopileatus*	87.85	90	Shevale and Deshmukh (2016)
	(b) Cauliflower leaves (80%) and paddy straw (20%)		86.86	90.80	
	(c) Paddy straw (100%)		89	90	
4.	Grape marc and wheat straw (1:1)	*Pleurotus ostreatus* LGAM 104	NA	98.03	Koutrotsios et al. (2021)
5.	Grape marc and wheat straw (1:1)	*Pleurotus citrinopileatus*	NA	78.52	Koutrotsios et al. (2021)
6.	(a) Peapods (20%) and paddy straw (80%)	*Pleurotus ostreatus*	90	93	Singh and Singh (2014)
	(b) Peapods (30%) and paddy straw (70%)		90	96	
	(c) Cauliflower leaves (20%) and paddy straw (80%)		90	96	
	(d) Cauliflower leaves (30%) and paddy straw (70%)		90	96	

(continued)

Table 5.2 (continued)

S. No.	Fruit and vegetable waste valorized	Mushroom type	Moisture content (%)	Biological efficiency (%)	References
	(e) Redish leaves (20%) and paddy straw (80%)		90	96	
	(f) Redish leaves (30%) and paddy straw (70%)		90	98	
	(g) Paddy straw (100%)		91	91	
7.	(a) Peapods (20%) and paddy straw (80%)	*Pleurotus sapidus*	83	95.11	Singh and Singh (2012)
	(b) Peapods (30%) and paddy straw (70%)		83	96.88	
	(c) Cauliflower leaves (20%) and paddy straw (80%)		84	92.22	
	(d) Cauliflower leaves (30%) and paddy straw (70%)		88	93.44	
	(e) Redish leaves (20%) and paddy straw (80%)		87	94.44	
	(f) Redish leaves (30%) and paddy straw (70%)		86	96.66	
	(g) Paddy straw (100%)		90	90	
8.	Cassava peels	*Pleurotus ostreatus*	84.58–84.83	24–26	Kortei et al. (2014)
9.	Pomegranate peel and paddy straw (3:1)	*Pleurotus florida*	NA	8.031	Lalithadevy and Many (2014a, b)
10.	Winery and apple wastes	*Ganoderma lucidum, Lentinula edodes, Pleurotus ostreatus*	NA	20–28	Petre and Petre (2008) and Petre (2013)
11.	(a) Vegetable waste (50%) and paddy straw (50%)	*Pleurotus ostreatus*	85	NA	Komal et al. (2016)
	(b) Paddy straw (100%)		90	NA	
12.	Apple pomace and wheat straw (1:3)	*Pleurotus ostreatus*	89.88	8.8	Pathania et al. (2017)

[a]*NA* Data Not Available

agro-industrial waste for sustainable development that has an important role in modern society (Ivarsson et al. 2021). According to Ritota and Manzi (2019), the chemical makeup of the agri-food industry comprises lignocellulosic matter that is a well-suited substrate for the solid-state fermentation practice performed by mushrooms. Valorizing these lignocellulosic materials from food industry waste is a promising elucidation and ecological approach in reducing the influence of the waste on the environment. However, the different substrates from food industry waste can be utilized to produce *Pleurotus* spp., which can be an economic and favorable return to the industries.

Moonmoon et al. (2011) demonstrated that the production of *L. edodes* (shiitake mushroom) swiftly increases in Bangladesh due to its dietary and therapeutic status with great savor and extended shelf life. The researchers mentioned above produced *L. edodes* on sawdust augmented with diverse concentrations of 10%–40% of wheat bran, rice bran, maize and powder and their amalgamation ratio 1:1:1 to explore the mushroom's quantity, growth, and quality. Mushroom yield elevated at a specific limit and then decreased with each concentration of the supplement. However, it was concluded that sawdust augmented with 25% wheat bran produced a more significant number of fruiting bodies of *L. edodes,* that is, 35 per 500 g packet, the maximum biological yield of 153 per 500 g packet with 77% biological efficiency. In contrast, the best quality of the *L. edodes* was attained with 40% wheat bran augmentation. Hence, it can be assumed from the above findings that the quality of the mushrooms produced is not always dependent upon the amount of the substrate supplemented. In brief, the study reported that augmenting the sawdust with 25% and 40% wheat bran resulted in better yield and quality, respectively, of the *L. edodes*.

Pleurotus eous was cultivated on diverse food waste such as paddy, tur, jowar, soybean, wheat, bajra, and sunflower straw and scrutinized the significance of these wastes on the composition of the mushrooms grown and produced and bio-efficiency. The findings showed that *P. eous* grown on paddy straw contained a stipe weight of 1.10 g and bajra straw with a pileus weight of 5.98 g. The maximum yield of 820 g per kg of dry straw and biological efficiency of 82%, the protein content of 31%, the crude fiber content of 9%, ash content 7%, phosphorous content of 965 mg, and Fe content of 16 mg mushroom were observed from soybean straw. The mushroom fruiting body showed utmost moisture content of 91% from Jowar straw, while wheat straw showed 2.6% of fat content and carbohydrate content of 52% from sunflower straw (Telang et al. 2010).

Sardar et al. (2017) utilized low-quality food industry waste and investigated their nutritional value. The waste from the agro-industry included sugarcane bagasse, wheat straw, cotton leftover, corn cobs, and rice straw. The findings revealed that mushroom mycelium evolution was highest on cotton waste rather than on lignocellulosic materials. In addition, they exhibited enhanced biological efficiency, carbohydrates, total phenols, macro and micronutrients, proteins, fat content, and low levels of DPPH (2,2-diphenyl-1-picrylhydrazyl) activity. However, the study mentioned above suggested that cotton waste can be exploited to cultivate *P. eryngii*, which is a potent and lucrative substrate. Therefore, mushroom cultivation was also studied using cotton hulls and cotton stalks by Sardar et al. (2020).

A detailed account of mushroom production and the biological efficiency from agro-based waste materials is given in Table 5.3.

Two-phase olive mill residuals are an extremely lethal runoff in the form of slurry from the processing and refining of olives for olive oil production. The valorization of such waste can be exploited as a substrate for the production of palatable mushrooms. The researchers assessed the role of 15 fungal strains from five diverse species such as *Pleurotus cystidiosus*, *P. pulmonarius*, *P. eryngii, Agrocybe cylindracea,* and *P. ostreatus* on mixtures of olive mill waste and wheat straw. The maximum biological efficiency attained was 135% and 125% from *Pleurotus* spp. and *A. cylindracea*. However, it has been confirmed that oil mill waste substrate can act as a potent waste valorization approach for mushroom cultivation and subsequently plays a role in recycling hazardous effluent from food industries (Zervakis et al. 2013). Another report demonstrated by Altieri et al. (2009) revealed that olive mill residuals could be exploited as a potent substrate to cultivate *Agaricus bisporus* (Lange) Sing at a large scale. Avni et al. (2017) explored diverse species of *Pleurotus* grown on olive mill waste to determine their β- and α-glucan content. It was found that the stipe contained more glucan content than pileus, and olive mill waste was judged as a suitable substrate for enhancement of glucan content in mushrooms. *P. sajor-caju* (Fr.) Singer was produced on various agriculture wastes, including pigeon pea leaves, pigeon pea stalks, groundnut haulms, soybean straw, cotton stalks, wheat straw, etc. Pigeon pea stems, cotton stems, and wheat straw alone or amalgams showed best cultivation rates than other substrates used. However, *P. sajor-caju* showed promising results in converting the lignocellulosic materials from waste into edible mushrooms (Mane et al. 2007).

5 Conclusions and Future Perspectives

Fruits and vegetables have been considered an essential nutritional diet in our daily regime that generates massive amounts of waste upon consumption. The waste generated is in the form of peels, skins, seeds, stalks, stems, leaves, and straw, mainly in the form of lignocellulosic materials that pile up in nature and is unexploited. The waste generated from domestic and industrial fruit and vegetable processing has enormous potential to be utilized in some value-added products. Furthermost, such practical implications of fruit and vegetable waste valorization include the cultivation of edible mushrooms. Edible mushrooms possess significant protein, minerals, vitamins, fiber, and carbohydrate content but are lower in fat content and possess the ability to degrade lignocellulosic materials through solid-state fermentation.

Table 5.3 Valorization of agro-industrial waste for the production of mushrooms and their biological efficiency

S. No.	Agro-based waste materials used as substrate	Mushroom type	Biological efficiency (%)	References
1.	Sugarcane bagasse	*Lentinula edodes*	130	Familoni et al. (2018)
		Pleurotus cystidiosus	50	Adedokun et al. (2013)
		Pleurotus florida	76	Kumar et al. (2015)
		Pleurotus ostreatus	66	Iqbal et al. (2016)
2.	Sugarcane straw	*Pleurotus ostreatus*	104	Vieira and de Andrade (2016)
3.	Sugarcane residue and bagasse	*Pleurotus ostreatus*	107	Aguilar-Rivera and De Jesús-Merales (2010)
4.	Wheat straw	*Agaricus bisporus*	51	Girmay et al. (2016)
		Pleurotus eryngii	48	Telang et al. (2010)
		Agrocybe cylindracea	61	Pardo-Giménez et al. (2020)
		Pleurotus ostreatus	53	Pardo-Giménez et al. (2020)
		Pleurotus ostreatus	86	Vieira and de Andrade (2016)
		Pleurotus florida	66	Sardar et al. (2017)
5.	Brassica straw	*Pleurotus citrinopileatus*	70	Shevale and Deshmukh (2016)
6.	Sunflower stalk	*Pleurotus eous*	62	Telang et al. (2010)
		Pleurotus sapidus	46	Telang et al. (2010)
7.	Olive mill waste and wheat straw	*Pleurotus ostreatus* and *Pleurotus pulmonarius*	85	Ruiz-Rodriguez et al. (2010)
8.	Two-phase olive mill waste	*Pleurotus* species	120–135	Zervakis et al. (2013)
9.	Olive mill by-products	*Pleurotus ostreatus*	72	Koutrotsios et al. (2021)
10.	Coffee pulp	*Pleurotus eous* and *Pleurotus flabellatus*	NA	Parani and Eyini (2012)
11.	Coffee husk	*Pleurotus ostreatus*	NA	da Luz et al. (2012)
12.	Corn cob	*Pleurotus cystidiosus*	50	Hoa et al. (2015)
		Pleurotus eryngii	52	Sardar et al. (2017)
		Pleurotus ostreatus	66	Hoa et al. (2015)
13.	Rice husk	*Pleurotus pulmonarius*	2–20.2	Caroline and Ekaette (2012)
14.	Rice straw	*Lentinula edodes*	49	Cristiane et al. (2015)
		Lentinus sajor-caju	78	Valverde et al. (2015)

(continued)

Table 5.3 (continued)

S. No.	Agro-based waste materials used as substrate	Mushroom type	Biological efficiency (%)	References
		Hericium erinaceus	34	Koutrotsios et al. (2014)
		Pleurotus citrinopileatus	89	Patil (2013)
15.	Barley straw	*Lentinula edodes*	89	Hassan (2007)
		Pleurotus ostreatus	21	Prasad et al. (2018)

[a]*NA* Data Not Available

Furthermore numerous fruit and vegetable waste materials such as banana leaves, banana pseudostems, grape marc, peapods, cauliflower, reddish leaves, carrot, onion, cucumber, potato peels, papaya peels, and pumpkin peels have shown the cos-effective and efficient mushroom production through various biotechnological interventions. However, in most of these studies, FVWs could not produce mycelium in appreciable quantity when used alone. But, on the other side, there is a nutrient enrichment and increase of yield of fruiting bodies of mushroom when these FVWs are used in combination with agro-waste materials as the substrate.

Mushrooms have been commercially grown and marketed due to their great therapeutic and nutritional values such as antimicrobial, antitumor, antihypertension, anti-hypocholesterolemia, antidiabetics, no genotoxicity, and many more. Their health-promoting factors have prompted researchers worldwide to exploit readily available materials for their production to achieve sustainability. In this regard, extensive literature is not available on the valorization of FVW for mushroom production at an industrial scale. This needs to be explored to eradicate the waste disposal problem and combat malnutrition and food insecurity that persists worldwide. A simple integrated strategic approach must be framed to valorize fruit and vegetables leftover for the cultivation of mushrooms from lab to industrial scale.

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Chapter 6
Fruit and Vegetable Wastes as Livestock Feeds

B. Lalramhlimi, Debmala Mukherjee, Ivi Chakraborty, Nilotpal Ghosh, Arup Chattopadhyay, and Ramesh C. Dey

Abstract The farmers have to deal with a difficult time disposing surplus and rejected farm produce during the peak production season. Due to certain inappropriate and/or inadequate pre- and post-harvest management factors, the fruits and vegetables are spoilt. Further, a large amount of highly perishable wastes are obtained from agro-based industries through different series of processes like sorting, grading, processing, packaging, and distribution. Kitchen wastes also contributed majorly from fruits and vegetables. Increasing food waste generation, improper waste disposal, and poor waste management strategies have an adverse environmental issue, especially in developing countries. The search for feed substitutes due to decreasing fodder production and higher input for production pave ways for efficient waste disposal of fruits and vegetables by creating the perfect solution for developing feed resources. The study on the potential of fruit and vegetable wastes is gaining importance due to their rich nutrient and phytochemical contents, rendering them suitable as animal feed substitutes while providing a complete supplement of nutrients required for the normal growth and development of livestock. It also leads to lower cost of feeding, resulting in increased earnings for farmers. Thus livestock feed production using fruit and vegetable wastes is an eco-friendly, sustainable, and efficient waste management option. This review demonstrates the importance of fruit and vegetable wastes as an alternative source of phytochemicals and nutrients for livestock feeds.

Keywords Livestock feeds · Fruit and vegetable wastes · Waste management

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1 Introduction

The livestock sector contributes significantly to the welfare of the rural population globally by employing a substantial portion of the labor force; improving poor farmers' economic, social, and food security; and providing a significant portion of draught power required to plow cropland. The livestock sector in India is one of the largest in the world. The livestock industry is vital to Indian economy. A total of 20.5 million people rely on livestock for their survival. Small farm households exhibit a 16% increase in income, compared to a 14% increase for all rural households. It supports two thirds of India's rural population and employs roughly 8.8% of the country's population. It contributes 4.11% gross domestic product of India and 25.6% of the total agricultural gross domestic product (Anonymous 2019). The 20th All India Livestock Census revealed a total livestock population of 535.78 million, an increase in 4.6% over the previous Census in 2012 (GOI 2019). In most developing countries, demand for animal products such as milk, meat, eggs, wool, leather, etc. is fast expanding. By-products such as dung and other animal wastes have been utilized to make good farmyard manure, biogas, dung cakes, and other products, which are still widely available in rural areas.

With the increasing livestock population, there is pressure on livestock feed availability. Many developing countries face feed shortages. A deficit of 25, 117, and 159 million tons of concentrates, crop wastes, and green forages have been reported in India, constituting a deficit of 32, 25, and 20% of the requirement, respectively (Kiran et al. 2012). Nonavailability of land for fodder production, increase in prices of feed ingredients, increase in the cost of fossil fuels, etc. contribute to shortages of livestock feed resources to fulfill the needs and demands. The combined effects of climate change, land degradation, cropland losses, water scarcity, and the high cost of inputs such as fertilizer and pesticides have also increased the cost of feed ingredients such as cereals (Wadhwa et al. 2015). So, it becomes a big challenge in India to fulfill the feed demand for the huge livestock population from the same land and water resources. New nonconventional alternate feed resources could be crucial in addressing this challenge. The search for feed substitutes and waste disposal of fruits and vegetables and its utilization create the perfect solution for developing feed resources using fruits and vegetable wastes. These wastes can be super food, full of essential elements, and phytochemicals that meet quality and sustainable feeds. Furthermore, their utilization can lower the cost of feeding, resulting in increased earnings for farmers.

2 Agro-Wastes as Livestock Feeds

In many countries, a significant amount of wastes (fruits and vegetables) are generated through sorting, processing, packaging, distribution, and consumption, which are then disposed of in landfills or rivers, contaminating the environment. They are also used for the preparation of compost. Together with the Philippines, China, and the United States, India generated a total of approximately 55 million tons of fruit and vegetable wastes (FVWs) (Wadhwa and Bakshi 2013). In India, during peak growing season, vegetables and fruits are spoilt in various stages to the extent of 20–25% due to improper post-harvest management (Chakraborty and Chattopadhyay 2018). The nonedible components, such as seeds, peels, skins, pods, etc., of fruits and vegetables are obtained as processing wastes, accounting for about 10–60% of the total weight of the fresh produce. Such wastes have been growing in volume, posing environmental and disposal issues and loss of significant biomass and nutrients (Sharma et al. 2016). By-products derived from FVWs proved to be good sources of phytochemicals (carotenoids, phenolics, and flavonoids), antimicrobials, antioxidants, dietary fats, or vitamins that possess favorable nutritional components and technological activities (Schieber et al. 2001; Fernandez-Lopez et al. 2008).

Therefore, alternate feed resources using fruit and vegetable wastes (FVWs) can potentially substitute conventional fodder while fulfilling the nutrient needs of livestock to maintain stable production, productivity, and profitability. For example, in baby corn, after the cob is removed for human consumption, the husk waste can be given raw, ensiled alone after wilting or ensiled with cereal straw. When compared to traditional maize fodder, these are more acceptable and palatable. The FVWs can be incorporated into the diet of livestock either fresh, dried, ensiled, or fermented form, while supplying basic nutrient needs. Livestock feed production using FVWs is an eco-friendly, efficient waste and pollution management option by efficiently reducing methane gas emissions. Devendra (1997) had given the grouping of nonconventional agro-wastes suitable for animal feed as follows:

- Energy and protein concentrate: These are the high energy and high protein feed for animals like poultry, pigs, ducks, cattle, etc. For example, soybean meal, coconut cake, rice bran, and poultry litter.
- Good-quality crop residues: These are also high protein and high energy feeds for animals like pigs, ducks, cattle, etc. For example, cassava peels, cereal grain waste, animal waste.
- Medium-quality crop residues: These are medium protein feed for pigs and ruminants.
- Low-quality crop residues: These are high fiber and low protein feed for ruminants.

A massive amount of waste is derived from fruits and vegetables through agro-industrial processing, as shown in Table 6.1.

2.1 Methods of Processing: Waste to Feed

Feeds are processed to aid handling and preservation and improve their nutritional value by enhancing digestibility or inactivating specific growth inhibitors. For example, soybean is a high-quality vegetable protein source; however, it cannot be given raw to animals due to high anti-nutritive factors (mainly trypsin inhibitors and

Table 6.1 Amount of wastes derived from fruits and vegetable processing

Commodity	Component of wastes	Wastes amount (%)	References
Apple	Pomace, peel, seed,	25	Wadhwa and Bakshi (2013)
Citrus	Peel, rag, seed	50	Gupta and Joshi (2000)
Mango	Peel, stones	45	Gupta and Joshi (2000) and Mitra et al. (2013)
Grape	Stem, skin, seed	20	Gupta and Joshi (2000)
Pineapple	Skin, core	33	Ketnawa et al. (2011) and Choonut et al. (2014)
Guava	Peel, core, seed	10	Gupta and Joshi (2000)
Banana	Peel	35	Gupta and Joshi (2000)
Dragon fruit	Rind, seeds	30–45	Cheok and others (Cheok et al. 2018)
Durian	Skin, seeds	60–70	Siriphanich and Yahia (2011)
Mangosteen	Skin, seeds	60–70	Chen et al. (2011) and Ketsa et al. (2011)
Papaya	Rind, seeds	10–20	Lee et al. (2011) and Parni and Verma (2014)
Passion fruit	Skin, seeds	45–50	Esquivel et al. (2007) and Almeida et al. (2015)
Rambutan	Skin, seeds	50–65	Sirisompong et al. (2011) and Issara et al. (2014)
Tomato	Skin, core, seed	20	Gupta and Joshi (2000)
Potato	Peel	15	Gupta and Joshi (2000)
Onion	Outer leaves	10	Wadhwa and Bakshi (2013)
Pea	Shell	40	Gupta and Joshi (2000)
Jackfruit	Rind, seeds	50–70	Saxena et al. (2011)

lectins) that interfere with soy protein digestion and absorption, lowering animal growth performance and value. These anti-nutrients can be removed or destroyed by heat treatment. Similarly, most generated FVWS are not suitable for animal feed in their natural state. Therefore, they require further processing to improve palatability, and specific techniques/methods are involved in executing the process. The techniques of converting food waste to produce feed include boiling, silaging, drying, low-pressure frying, high temperature dry (Sugiura et al. 2009), pelleting, grinding (NRC 1973), and microbial fermentation (Cousin 1980). Therefore, the nutritional value of wastes is highly dependent on the methods of processing and should be taken into consideration before starting feed processing.

3 Fruit Wastes as Livestock Feeds

This section discusses livestock feeds produced from various tropical and temperate fruits (Table 6.2).

Table 6.2 Incorporation of fruits and their parts in the diets of livestock

Fruits	Feeds/product	Dosage	Results	References
Mango	Processed (soaked/sun-dried) whole mango fruit	37.5% in the diet of sheep	Growth improvement	Ibrahim et al. (2020)
	Macaroni, jam, prepared from mango peel			Ravani and Joshi (2013)
Apple	Ensiled apple pomace	15% in the diet of lactating multiparous Holstein cows	Improved milk yield or its components	Ghoreishi et al. (2007)
	Apple pomace	Replaced 33% of concentrate mixture in the diet of crossbred (Red Sindhi × Jersey) cows	Increased solid not fat (SNF) content while milk production showed no significant effect	Tiwari et al. (2008)
Pineapple	Ensiled pineapple waste supplemented with a protein source and fresh fodder (2.5 kg)	70% in the diet of steers	Lower feeding cost and high daily weight gains (1 kg/day)	Geoffroy et al. (1984)
Citrus	Ensiled citrus	50% in the diet of steers	Can substitute 50% of the ground maize without lowering gains in body weight, quality, or carcass yield	Hendrickson and Kesterson (1965)
	Citrus pulp ensiled with wheat straw and poultry litter	15–20% dry matter (DM) in the diet of sheep	Increased level of feeding results in lower palatability	Migwi et al. (2001)
Banana	By-product silage	50% green banana +50% bunch + additives, 10% molasses, and 7% beet pulp	Better silage with pleasant smell and good visual characteristics	Alvarez et al. 2015
	Banana leaf meal	40% in the forage-based diet of Zebu cattle and sheep	Increased weight gains and feed efficiency	Garcia et al. (1973)
	By-product silage	Fresh banana by-product +4% cornmeal	More significant total weight gain, average daily weight gain, body diagonal length, height at the hip, hip width, and rump length	Xue et al. 2020
	Ripe banana peels	14–21 kg fed on dairy cows	Produce more milk	Dormond et al. (1998)

(continued)

Table 6.2 (continued)

Fruits	Feeds/product	Dosage	Results	References
	Banana peels	15–30% to the feed of grass to fed Zebus	Improved weight gain	Hernan et al. (Hernan Botero et al. 2000)
Guava	Guava agrotoindustrial wastes	30% in the diet of animals (Santa Ines breed)	Lowers cholesterol levels while increasing total thyroxine and total triiodothyronine levels in the blood, improving the animals' metabolism	Costa et al. (2018)
Jackfruit	Jackfruit residue silage Nutrient-enriched animal feed by supplementing nitrogen and fermenting with yeast (*Saccharomyces boulardii*) and LAB (*Lactobacillus acidophilus*)	50% in the finger millet straw diet of Mandya lambs	Can substitute 50% of finger millet straw without altering digestibility of nutrients and dry matter intake	Arun et al. (2020), Ajey (2013) and Akter and Haque (2019)
Dragon fruit fruit	Fruit peel	9% bio- supplement of dragon fruit peel in the diet of rabbits	Improve overall performance in weight, intake of feed, and conversion of feed	Prastiya and Yusuf (2021)

3.1 Mango Wastes

India is the largest producer of mango (*Mangifera indica* L.) pulp, contributing 42.7% to world production. Mango is made up of 33–85% pulp, 7–24% peel, and 9–40% seed on a fresh weight basis, and 35–60% of total fruit weight during processing are produced as a by-product (Mitra et al. 2013; Ayala Zavala et al. 2011; Siddiq et al. 2017; Lopez-Cobo et al. 2017). Mango agro-industries generate a large quantity of by-products and agro-industrial wastes. The wastes available after processing include cull fruits, mango peels, deoiled mango kernel meal, and mango kernel meal, which contains 6–16% oil on a dry matter basis (Wadhwa and Bakshi 2013). The relative proportion of different parts varies with varieties and stages of maturity. Because of 25–50% of seed and peel in a fruit, massive waste is generated during industrial processing. Such by-products have a severe disposal problem, so a commercial utilization for mango peel and kernels is sought. Both seed and peel are rich in many valuable compounds that can be utilized as different livestock feed (Mitra et al. 2013).

3.1.1 Mango Wastes as Livestock Feeds

Fresh, dried, or ensiled mango peels can be fed to livestock. They are pleasant and regarded as energy feed because of their high sugar content (13.2%); however, the high moisture and acidity of fresh peels may prevent their use in ruminants. Low protein content also resulted in the requirement of nitrogen or protein source addition to facilitate efficient energy use in the diet. The peels of mangoes were combined with legumes and rice straw to aid fermentation and generate excellent silage. The dry matter digestibility of mango peels ensiled with rice straw was 60%, which increased when the leaves of *Leucaena* were added to the diet (Sruamsiri and Silman 2009). Ibrahim et al. (2020) found that including up to 37.5% processed (soaked/sun-dried) whole mango fruit in the ration as a substitute for maize bran resulted in considerable gains in the growth performance of sheep without compromising the well-being of the sheep. Mango seed kernels can be added to the concentrate mixture up to 50% without causing any problems (Gohl 1982). The dried seed kernels have dry matter digestibility of 70% in sheep, but consumption was low (1.2% of body weight), owing to the presence of tannin.

3.2 Pineapple Wastes

The juice extraction of pineapple produces wastes such as crowns, skins, pomace, and other debris. The amount of garbage generated as by-products was 33% through processing (Wadhwa and Bakshi 2013). On a dry matter basis, raw pineapple waste has 4–8% crude protein, 60–72% neutral detergent fiber, 40–75% soluble sugars (70% sucrose, 20% glucose, and 10% fructose), and pectin, but deficient in minerals (Muller 1978; Pereira et al. 2009). The addition of minerals and protein can avoid adverse effects on health and productivity. Drying or ensiling can be used to preserve fresh pineapple cannery waste. The solid residue “pineapple bran” leftover after the crowns and skins have been crushed and macerated is also suitable for livestock feed. It is also made from the stump leftover from the bromelain extraction process. It can be fed fresh, ensiled, or after drying to livestock.

3.2.1 Pineapple Wastes as Livestock Feeds

Pineapple waste is very appetizing and easily digestible (73–75% organic matter digestibility) in cattle, sheep, and goats (Muller 1978). Animals prefer fermented pineapple waste over fresh pineapple waste as it is lesser acidic (Sruamsiri 2007). The digested slurry through anaerobic digestion of pineapple peel can be used as an animal, poultry, and fish feed (Rani and Nand 2004). Pineapple wastes can replace roughage in the diet and cereals in the diet of meat animals (Muller 1978; Geoffroy 1985). Ensiled pineapple waste supplemented with a protein source, fed to steers for up to 70% of their diet, and 2.5 kg fresh fodder resulted in high daily weight gains (1 kg/day) and lower feeding costs (Geoffroy et al. 1984). It also can replace up to 60% of maize silage without compromising daily weight gains (Prado et al. 2003). The feed cost was lowered by silage comprised of 80% pineapple wastes and 10% poultry litter with molasses and additives. Pineapple waste combined with rice straw can replace up to 50% of the roughage in a dairy cow's total mixed feed without harming milk production (Sruamsiri 2007).

3.3 Apple Wastes

There is abundant apple production in India, with approximately 2.27 million tons in 2018–2019 (NHB 2019). Out of this, the damaged and spoilt apples, which are not marketable, account for 30–40%, and juice extraction processing accounts for 20–40%. One of the most suitable feeds for livestock is the apple pomace which is the residue left after extraction of the juice. After drying, the apple pomace is found to contain a significant amount of crude protein (7.7%) and ether extract of 5.0% (Wadhwa and Bakshi 2013). It was also found to possess a substantial level of polyphenols, primarily found in the skin/peels, and only a small percentage of which is extracted into juice (Schieber et al. 2001). The vitamin and protein contents can be increased by growing yeast on apple pomace (Hang 1987). It was reported that the co-culture of *Candida utilis* and *Aspergillus niger* on dried and pectin-extracted apple pomace increased the protein content by 20% and 17%, respectively (Bhalla and Joshi 1994). The phenolic components have been proven to have strong antioxidant properties in vitro (Lu and Foo 2000), implying economic potential (Schieber et al. 2001).

3.3.1 Apple Wastes as Livestock Feeds

The apple pomace, when dried or ensiled, has shown to be an excellent livestock feed. For lactating dairy cows, it can provide 1.86 M Cal metabolizable energy (ME) and 1.06–1.12 M Cal net energy (NE)/kg dry matter (NRC 2001). Incorporating ensiled apple pomace at 15% in the ration of lactating multiparous Holstein cows resulted in improved milk yield or components (Ghoreishi et al. 2007). Furthermore, apple pomace added with urea resulted in weight reduction and lambing performance in ewes, according to Rumsey and Lindahl (1982). The addition of straw in cows' ration could help reduce these adverse effects (Rumsey et al. 1979).

3.4 Citrus Wastes

The amount of citrus wastes (peel, rag, seed, etc.) generated as by-products amounted to 50% during processing (Wadhwa and Bakshi 2013). Juice extraction in processing industries requires an extensive amount of fruits (citrus) that result in agro-industrial by-products such as fresh pulp, fiber pectin, dried pulp, molasses, cold-pressed oils, pulp wash, juice pulps, ethanol, seed oil, pectin, limonoids, and flavonoids (Bampidis and Robinson 2006; Siliha et al. 2000; Braddock 1995; Martinez and Carmona 1980). Citrus pulp is obtained after juice extraction (50–70% f/w), containing 60–65% peel, 30–35% internal tissues, and 10% seeds (Crawshaw 2004). Citrus pulp, commonly extracted from oranges, grapefruits, and lemons, contains 5–10%, 6.2%, 10–40%, 54%, 1–2%, and 0.1% of crude protein, ether extract, soluble fiber (pectins), water-soluble sugars, calcium (due to the addition of lime), and phosphorus, respectively (Crawshaw 2004; Bakshi and Wadhwa 2013). Citrus pulp also contains many trace elements, although their concentration is significantly lower than the ruminant's maximum tolerance level. The peels and seeds of citrus fruits have been high in antioxidants (Bocco et al. 1998).

3.4.1 Citrus Wastes as Livestock Feeds

Ruminants can easily ferment fiber so that citrus by-products can be added to the ration of ruminants. Dairy cattle eat fresh citrus readily, yet storage, transport, and handling concerns restrict its utilization (Lundquist 1995). Citrus pulp is usually dried before feeding to animals. It should be gradually introduced into a diet to allow the animals to get used to its distinct smell and taste (Bampidis and Robinson 2006). The daily ration of 50–60 kg fresh citrus pulp can be fed to adult crossbred cattle. Due to its excellent organic matter digestibility (85–90%) and energy availability (2.76–2.9 Mcal ME (metabolizable energy)/kg DM (dry matter) and 1.66–1.76 Mcal NE (net energy)/kg DM) for lactating dairy cows, the dehydrated citrus pulp is utilized as a grain alternative in concentrate diets. ME availability is similar to barley and is 85–90% of maize (NRC 2001; Bampidis and Robinson 2006). It can substitute 20% concentrate in dairy cattle (Assis et al. 2004) and up to 30% of concentrate in lactating ewes (Fegeros et al. 1995) without influencing dry matter intake and digestibility rumen metabolites, milk yield, or milk protein and fat contents. Citrus pectins break down quickly and extensively, yielding acetic acid, which is less likely than lactic acid to produce a pH drop, resulting in acidosis (Wing 2003). Extended rumination of citrus pulp produces vast amounts of saliva, which has a buffering impact on rumen pH due to its high fiber content. Citrus pulp is thus seen as a safer feed than cereals for animals fed high concentrate, low roughage diets, such as high yielding dairy cows (Crawshaw 2004). High-level feeding can produce a sufficient amount of butyric acid to enlarge, and keratisine rumen papillae inhibit the absorption of nutrients and weaken the performance of animals (Brugere-Picoux 2004).

The fresh citrus pulp should be combined with grass, hay, sugarcane bagasse, or cereal straw before ensiling to increase the dry matter content. Waste from fruit juice (mostly sweet lime) without peels can be ensiled in a 70:30 ratio with wheat or rice straw to produce excellent silage (Bakshi et al. 2007). The odor of ensiled citrus pulp is pleasant, and cattle easily consume it. Citrus molasses are a by-product of citrus juice extraction, a dense dark brown to practically black liquid with a thick consistency obtained after the fresh pulp is mixed with lime and pressed. It has a bitter taste due to flavonoids (naringin), but beef and dairy animals readily accept it (Hendrickson and Kesterson 1965). When given ad libitum, an intake of 3 kg/day was reported in cattle (Gohl 1978). It could substitute 50% of the ground maize in a fattening steer's diet without lowering body weight increase, quality, or carcass yield (Hendrickson and Kesterson 1965).

3.5 *Banana Wastes*

Banana production in India is high, contributing about 17.3% of world production. The processed bananas contributed 35% peel as wastes (Ajila et al. 2012). About 30–40% of the total banana crop is discarded due to poor quality and could raise livestock (Babatunde 1992). Small, broken/cracked bananas, banana peels and foliage, immature stalks, and pseudostems are all examples of banana trash that can be fed to livestock. Molasses, grass, legumes, rice bran, and other ingredients can be used to ensile fresh banana and plantain fruit. Fruits that are still green are more accessible to ensile than those that are already ripe. Banana leaves have roughly 15% dry matter and 10–17% crude protein, while pseudostems have 5–8% dry matter and 3–5% crude protein. The neutral detergent fiber and acid detergent fiber range from 50 to 70% and 30–40%, respectively.

Moreover, 8% of polyphenols and very few condensed tannins are present in banana leaves (Marie-Magdeleine et al. 2010). The peels of ripe bananas contained 1.95 ± 0.14% crude proteins, 5.93 ± 0.13% crude fat, 8.37 ± 0.18% crude fiber, and 11.82 ± 2.17% carbohydrate. It is also found to contain an appreciable amount of phosphorus, iron, calcium, magnesium, and sodium with low zinc, copper, potassium, and manganese (Hassan et al. 2018).

3.5.1 Banana Wastes as Livestock Feeds

The banana wastes are readily eaten by animals such as goats (Alvarez et al. 2015), dairy cattle (Katongole et al. 2008), beef cattle (Xue et al. 2020), and rabbits (Ekwe et al. 2011) for their average intake and digestibility. Banana leaves were chopped and sun-dried to prepare leaf meal which was incorporated up to 40% in the fodder diet on a dry matter basis resulting in high weight gains and efficiency of feed of Zebu sheep and cattle (Garcia et al. 1973). The ensiled dried foliage with dried broiler litter in a 40:60 ratio and rehydrated with either molasses or whey included at 15% (Khattab et al. 2000) and ensiled foliage with wheat straw (75:25) with molasses and urea (Baloch et al. 1988) could substitute 50% of fodder (green maize) in the food of lactating cows/buffaloes without changing milk production. Cattle fed with fresh banana wastes and cornmeal silage mixture tended to have a more significant total weight gain, average daily weight gain, height at the hip, diagonal body length, the width of the hip, and length of the rump (Xue et al. 2020).

The addition of 15–30% banana peels to the feed of grass-fed Zebus significantly increased weight without producing health concerns or compromising palatability (Hernan et al. Hernan Botero et al. 2000).

3.6 Guava Wastes

Guava agro-industrial waste comprises pulp and primarily seeds, containing a lot of fibrous debris and unsaturated fatty acids (Uchoa-Thomaz et al. 2014). The amount of wastes (peel, core, seed, etc.) generated as by-products amounted to 10% through processing (Wadhwa and Bakshi 2013). As a result, guava agro-industrial waste has high protein content (7.9–9.6%), a fat content of 10.5–16%, and a raw fiber content of 53.6–67.7% (Chang et al. 2014).

3.6.1 Guava Wastes as Livestock Feeds

The addition of guava agro-industrial waste up to 30% of the diet lowers cholesterol levels while increasing total thyroxin and total tri-iodothyronine levels in the blood, improving the animal's metabolism (Costa et al. 2018). Furthermore, guava agro-industrial waste constituting up to 30% of the lamb diet did not affect meat performance, sensory characteristics, or physicochemical qualities (Nobre et al. 2020).

3.7 Grape Wastes

Grapes are the world's most important fruit crop, where wine and juice wastes constitute the maximum waste from grapes. The winery waste and other wastes of grapes produce 2.5–7.5% grape stalks, grape pomace (15% dry; wet up to 25–45%), 3–6% grape seeds, and 3.5–8.5% yeast lees. Yeast lees are the residual particles and yeast that settle at the bottom of the wine vat. The waste such as grape pomace accounts for roughly 20% of the weight of the grapes processed (Schieber et al. 2001). It contains high sugar (15%), 0.9% phenolics/pigments (red grape pomace), tartarate (0.05–0.08%), and fiber (30–40%). Flavonoids are abundant in grape skins and seeds, which act as antioxidants chemically inhibiting the oxidation process and as free radical scavengers (Brenes et al. 2008). However, it can be damaged when pomace is treated at a high temperature. Grape peels and skins are also high in polyphenols and dietary fiber, according to studies. Grape seeds include phenolics in the range of 4–6% and oil in the range of 12–17% and high in omega-6 fatty acid (76%) and linoleic acid. Grapeseed oil is also abundant in polyphenolics and unsaturated fatty acids (Jayaprakasha et al. 2001; Llobera and Canellas 2007).

3.7.1 Grape Wastes as Livestock Feeds

Grape pomace provides crude protein and ether extract in the range of 9–12% and 5–7%, respectively, with low ME (1.06 Mcal/kg DM) and NE (0.69 Mcal/kg DM) for lactating dairy cows (NRC 1989). Grape stalks after fermentation with fungal strains can be used as ruminant feed in the form of single-cell protein or as a component in feed (Nicolini et al. 1993). The results showed that when lignin content was removed through fungal treatment, the cellulose was more available to rumen microbes. The fermented product has a similar dry matter digestibility to forage (54–60%) due to its low lignin concentration and high protein content (Wadhwa and Bakshi 2013).

3.8 Papaya Wastes

The trash from papaya processing plants is suitable for replacing animals' feed (Koubala et al. 2014). However, a lot of agricultural waste is produced because of the high amount of papaya production with an estimated 30–50% cull rate (Heller et al. 2015).

3.8.1 Papaya Wastes as Livestock Feeds

Papaya peels contain polyphenols and minerals that are beneficial to animals' health. Thus they can be included in their diets. Silage is a typical way for preserving fresh forage for use as feed, and it has been claimed that this fermentation approach can also be used to store and prepare papaya peel residue. In general, silage preservation can be accomplished by producing enough acid to prevent undesired microbe activity under anaerobic conditions. Natural lactic acid bacteria production is beneficial to silage fermentation and can also affect its quality. Yang et al. (2016) also suggested that papaya peel can be used as silage due to the abundant nutrients and lactic acid bacteria. Papaya seed is a waste product that can be fed to livestock to substitute commercial livestock feed ingredients (Ayodele et al. 2019). The nutrient profile of papaya seed meal revealed the presence of bioactive components that can be used as feed additives in animal production and to improve human health (Kolu et al. 2021).

3.9 Avocado Wastes

Avocado waste includes significant levels of beneficial substances, including polyphenols, produced during the preparation of avocado for human use. According to

Rodriguez-Carpena et al. (2011), the significant antioxidant and antibacterial activity present in avocado is due to its high polyphenolic content. In addition, avocado also includes flavonoids, which have been shown to have a potent antibacterial effect against various resistant bacteria strains (Guil Guerrero et al. 2016).

3.9.1 Avocado Wastes as Livestock Feeds

In an experiment, Hernandez-Lopez et al. (2016) compared the muscle of avocado waste treated pigs to the muscle of pigs fed a control diet (without avocado waste). Fat composition, color stability, and oxidative stress were all examined in pigs. Significant results were obtained on the effect of avocado on intramuscular fat concentration and content, lowering lipid content in the longissimus thoracis et lumborum muscle. In addition, they raised unsaturated fat levels, according to the findings.

3.10 Underutilized Fruit Wastes

Due to its high pectin and cellulose content, jackfruit wastes are commonly processed into syrups and jellies. Rinds and other waste components of the fruits are fed to cattle as a nutritious source of food (Feili 2014). Animal feed can be made from the microbiological digestion of jackfruit waste. Ajey (2013) generated a dry powder product from jackfruit waste that contained moisture (5.42%), protein (23.81%), crude fiber (22.63%), crude fat (6.37%), carbohydrates (71.40%), and ash (6.5%) and lactic acid bacterium and yeast populations of 1.8×10^6 cfu (colony forming units)/g and 1.1×10^6 cfu/g, respectively. Jackfruit waste through microbial processing can be converted into enriched livestock feed. Condensed tannins (6.9%) and saponins (8.9%) were found in dragon fruit waste by-products as phytonutrients and are lesser than rambutan peel containing 12.0% condensed tannins and 10.5% saponins (Ampapon and Wanapat 2019), and mangosteen peel consisted of 15.3% condensed tannins and 11.9% saponins (Polyorach et al. 2016). Adding dragon fruit peel powder at 4% of total substrate, nonprotein nitrogen at 1% of the total substrate, and 40:60 roughage to concentrate ratio improved rumen fermentation end products and nutrient degradability and, most importantly, reduced methane production. As a result, dragon fruit peel powder could help ruminants produce more sustainably and cleanly while reducing methane emissions (Matra et al. 2021).

4 Vegetable Waste as Livestock Feeds

Vegetable wastes used as livestock feeds are discussed in this section (Table 6.3).

Table 6.3 Incorporation of vegetables in the diets of livestocks

Vegetables	Feeds/ product	Dosage	Results	References
Tomato	Tomato pomace	Replaced 15% of corn in the pelleted conventional diet of pigs	Higher concentration of PUFA *n*-6, PUFA *n*-3, PUFA, and the *n*-6:*n*-3 ratio in meat	Biondi et al. (2020)
	Tomato pomace	40% of the diet in multiparous goats	High milk production, better milk quality, and intermediate production cost	Mizael et al. (2020)
	Dried tomato pomace	32.5% of concentrate mixture	No negative consequences on animal wellbeing, milk output, and intake of dry matter	Belibasakis (1990) and Hussain et al. (1985)
Tomato and cucumber	Feed blocks	35% of the concentrate in the ration of dairy goat	Lower methane production and cost of animal feed. Increased (PUFA) polyunsaturated fatty acid content in milk without compromising nutrient utilization or milk yield	Romero-Huelva et al. (2012)
Potato	Raw potatoes	15–20 kg/day fed to dairy and beef cows	No harm to the well-being of animals	De Boever et al. (1983)
	Peel waste	Replace 25 and 50% of concentrate feed mixture in the diet of sheep	Improved in vitro dry matter disappearance and in vitro organic matter disappearance, reduced digestible crude protein intake, water intake	Tawila et al. (2008)
	Potato processing waste	Replace 20% of corn in the diet of Holstein cows Replace 20% of corn in the diet of steers	Decrease milk fat %. Decrease digestibility of acid detergent fiber, increase rumen pH	Onwubuemeli et al. (1985)
Carrot	Fresh carrot	20 kg fed to young bulls and 25 kg/day fed to dairy cows	No negative effects	Morel d'Arleux (1990)
		40% in the ration of steers	No negative consequences	Rust and Buskirk (2008)
	Dried carrot waste	50% on growing rabbit diet	No adverse effects on nutrient digestibility, productive performance, components of blood, and economically efficient	El-Medany et al. (2008)

(continued)

Table 6.3 (continued)

Vegetables	Feeds/ product	Dosage	Results	References
Cauliflower	Dried cauliflower	24% in the concentrate mixture diet alfalfa hay: concentrate(40:60)	Improved in vitro fermentation of rumen	de Evan et al. (2020)
Watermelon	Watermelon vine	Replace 25% of the berseem hay treated with *Penicillium oxalicum* in the diet of sheep	High yield of actual milk, 4% fat corrected milk, and milk contents.	Soliman et al. (2020)
Bottle gourd	Sundried ground pomace	Fifty % in the concentrate ration of ruminants	No negative result on the health or nutrient utilization of animals	Wadhwa and Bakshi (2013)

4.1 Tomato Wastes

Tomatoes are the most extensively processed vegetables, containing 40–60% nonstructural carbohydrates, 90–95% soluble sugars, and 5–10% pectin (ANSES 2008; Ventura et al. 2009). Culled tomatoes that are damaged, infected, undersized, deformed, or otherwise unsuitable for fresh market sale or processing and tomato pomace constitute the majority of tomato waste. Tomato pomace is made up of seeds, peels, and a small amount of pulp left after tomato processing and is given to livestock after being sun-dried and grounded. It also has 19–22% crude protein and 11–13% ether extract, with a 7–13% acid detergent lignin (ADL) concentration (NRC 1989; Bakshi et al. 2012). It contains a rich amount of the antioxidant "lycopene," which gives meat its red color. The seeds make up around 60% of the total waste and are a good source of protein (35%) and fat (25%), respectively (Zentek et al. 2014). According to reports, proteins present in tomato seeds have around 13% more lysine than soy protein. Unsaturated fatty acids, notably linoleic acid, are abundant in tomato seed oil. Carotenoids are lost in vast amounts as waste (Baysal et al. 2000).

4.1.1 Tomato Wastes as Livestock Feeds

Cull tomatoes are easier for ruminants to digest than tomato pomace because they contain more highly digested pulp and less fiber. Fresh tomatoes had 63% in vitro organic matter digestibility, resulting in a DE (digestible energy) value of 2.59 Mcal DE/kg DM. The high acid detergent insoluble nitrogen (ADIN) content was responsible for the protein's low Sacco degradability. Fresh cull tomatoes can be fed to male goats with ad lib ryegrass hay in amounts up to 1.5 kg without causing stomach problems (Ventura et al. 2009). Tomato pomace can be served fresh or stored for a longer time through solar drying or ensiling. However, due to the high moisture content, it cannot be ensiled alone. As a result, a 70:30 mixture of wheat or rice straws or maize stovers is advised. For lactating dairy cattle, tomato pomace provides 2.37 Mcal ME/kg dry matter and 1.43–1.53 Mcal NE/kg dry matter (NRC 1989). Multiparous dairy cows (26 kg milk/day) can be fed 32.5% dried tomato pomace in the concentrate mixture without affecting health, milk output, or dry matter intake (Belibasakis 1990). The solar-dried and grounded tomato pomace may substitute the concentrate combination in male buffaloes' diets without influencing dry matter intake, nutritional digestibility, urinary purine derivatives, microbial protein synthesis, and total volatile fatty acid (VFA) generation in the rumen (Bakshi et al. 2012). Another study had shown equivalent results in dry matter intake (3.74% BW), milk output (35 kg/day), and milk composition of dairy cows fed tomato pomace (fresh) maize silage and maize silage alone. Tomato pomace, either in fresh form, ensiled or dried, can substitute 50% of the required roughage (Caluya et al. 2003).

4.2 *Potato Wastes*

Farmers have a difficult time getting rid of surplus and rejecting potatoes during the peak harvest season. Because of the legal concerns, it cannot be easily disposed of even in areas like a waste land. Furthermore, due to the high cost, extra produce cannot be kept in cold storage. The farmers' only alternative is to feed them to the livestock. The phenolic contents are very high in aqueous peel extracts (De Sotillo et al. 1994). The fresh potatoes contain 65–75% starch (depending on the variety), crude protein (9.5%), and ether extract (0.4%) on a dry matter basis. Potatoes contain little amount of fiber components like neutral detergent fiber, neutral detergent solubles, and cellulose (Wadhwa and Bakshi 2013). Raw potatoes are unpalatable and have a laxative effect. Thus gradual feeding into an animal's diet should be done. Potatoes should be boiled or steamed to receive the most significant benefit from the starch they contain. Due to the solanine content in potato, sprouts should be removed before feeding potatoes to swine or fowl. Potatoes infected with fungus should never be fed to livestock. It has been reported that 150 mg/kg solanine is the safe limit in the feed material.

4.2.1 Potato Wastes as Livestock Feeds

For lactating dairy cows, potatoes have high ME (3.16 Mcal/kg DM) and NE (1.87 Mcal/kg DM) (NRC 1989). Raw potatoes can be fed to beef and dairy cows at a rate of up to 15–20 kg per day without causing harm to the well-being of livestock (De Boever et al. 1983). The tuber wastes can be cut and ensiled with fodder. To cook the potatoes, fermentation created adequate heat. Cattle can be fed the haulm if it is ensiled. Schluter (2002) pointed out that starch use is critical for adding potatoes in swine feed, necessitating steaming to improve digestibility. Stalljohann et al.

(2000) suggested that the pigs in the finishing period can be fed 1.5–3 kg steamed potatoes per day, or 10–20% of the total diet at 88% dry matter. Potatoes and by-products should be limited to 20–25% of the overall diet due to their low energy density and viscosity-increasing qualities.

4.3 Cauliflower Wastes

India alone is responsible for about 30% of global cauliflower production and nearly a quarter of the global cauliflower area. It is a vegetable with the greatest waste index, that is, the ratio of nonedible to edible fraction after harvesting (Kulkarni et al. 2001). It creates the most organic solid waste, which decomposes, producing a terrible odor. Cauliflower waste contained 17.32% cellulose, 9.12% hemicellulose, 5.94% lignin in a proximate analysis (Khedkar et al. 2017), and 16.1% protein (Wadhwa et al. 2006). Cauliflower contains more true protein, phenols, and total sugars when compared to pea vines. Nonreducing sugars made up the majority (76–85%) of total water-soluble sugars in these wastes (Wadhwa et al. 2006).

4.3.1 Cauliflower Wastes as Livestock Feeds

Cauliflower, cabbage, and radish leaves can be given to livestock fresh or after ensiling with wheat or rice straw in a 70:30 ratio (Wadhwa and Bakshi 2005; Bakshi et al. 2007). Ngu and Ledin (2005) studied the influence of feeding goats with wastes obtained from leaves of either cauliflower, cabbage, or Chinese cabbage along with para grass supplemented with soybean waste (soy milk production waste) for 136 days. They found that goats fed with cauliflower had the highest feed intake and gain in body weight (529 g dry matter/day and 87.5 g/day, respectively) compared to cabbage and Chinese cabbage.

4.4 Pumpkin Wastes

Food processing methods generate a huge amount of waste like pumpkin peels and seeds, which are nutrient and fiber-rich components and are a suitable alternative as feed materials. Carotenoids like beta-carotene, lutein, and zeaxanthin are abundant in pumpkin pulp (Scherz and Senser 2000). Fats and oils have a critical role in animal body cells, supplying vast amounts of energy reserves required to maintain a constant body temperature (Habib et al. 2015). *Cucurbita maxima* contain significant nutrients such as 28.68% carbohydrates, 33.48% proteins, 30.66% lipids, 3.98% ash, and 3.07% fiber (Karaye et al. 2013).

4.4.1 Pumpkin Wastes as Livestock Feeds

Fruit debris and farm residue created from pumpkin also benefit from being high in phenolic antioxidants. Because of their protective effects against oxidative stress and other degenerative diseases, these antioxidants may aid in the longevity of livestock and poultry (Mala and Kurian 2016). Pumpkin wastes incorporated in livestock feed aid in treating diabetes in livestock (Xia and Wang 2006). Seeds of selected pumpkin cultivars are processed into oil and oilcake in various parts of central Europe, which are high in protein and can be fed to pigs as a source of protein (Wetscherek-Seipelt et al. 1991). Although pigs have shown excellent digestibility when fed pumpkin pulp in animal studies, feeding large quantities can negatively affect fat consistency. Pumpkin waste such as pulp in dried form is reported as suitable swine feed; however, it is a waste of time and expense to dry the raw material.

4.5 Sugar Beet Wastes

The primary crops used to make sugar are sugarcane and sugar beet. Soil contamination in sugar beet is about 12.5%, and 2–2.5% constitutes the broken beetroots (Mirzaei-Aghsaghali and Maheri-Sis 2008). Pulp is obtained after the extraction of sugar, which is a valuable feed for ruminants. Exhausted beet pulp has a dry matter concentration of 8–15% depending on the method and hence requires dewatering, which is usually done through thermal drying and mechanical pressing (Schieber et al. 2001). The keeping quality of nutrient-dense feed can be increased significantly by ensiling crushed pulp (Heller 1998). Molasses is runoff syrup obtained at the end of the crystallization process that can also be utilized as feed.

4.5.1 Sugar Beet Wastes as Livestock Feeds

Beetroots damaged during the washing process can potentially be utilized to feed animals (Mirzaei-Aghsaghali and Maheri-Sis 2008). Kelly (1983) showed an insight on the use of sugar beet pulp in cattle nutrition. Most beetroots are consumed as a vegetable, with the remainder being processed into juice and food coloring. Sugar beet pomace after juice extraction from agro-industry makes up 15–30% of the raw material (Otto and Sulc 2001), and it can be used as fertilizer or feed (Schieber et al. 2001). Scouring is caused due to a high level of oxalic acid, which limits feeding fresh crowns and leaves above 10 kg/day while feeding ensiled leaves should not exceed 15 kg/day to cattle and more than 2 kg/day to sheep. In beet-top silage, the laxative action of beet tops is less evident. The best results are produced when beet-top silage is combined with lucerne hay (Wadhwa and Bakshi 2013).

4.6 Carrot Wastes

Carrot wastes generally consist of discolored carrots, vertical splits, and broken tips, later infected by fungus resulting in 30% of wastes (Kaur et al. 2021). Cull carrots obtained during the season of maximum harvest are mainly used as feed carrots and can be given fresh (whole/chopped), silaged, or dried to animals. Carrot tops and pomace after juice extraction are two more carrot derivatives that are sometimes fed to cattle. Fresh carrots have 10% crude protein, 1.4% ether extract, and up to 60% sugars, primarily sucrose (on a dry matter basis). Depending on the carrot variety, a good and quality carrot may contain 300–700 mg/kg dry matter, vitamin C, and 200–1000 mg/kg, dry matter carotene; orange carrots give β-carotene content of 200–1000 mg/kg dry matter (ANSES 2008). Carrot pomace obtained after juice extraction contains 7–8% crude protein, 1.8% ether extract, 4.3% total phenolics, and 64.3% total sugars (Bakshi and Wadhwa 2013). According to Sims et al. (1993), carrot processing waste such as pomace was reported to contain up to 80% of the carotenes present in carrots.

4.6.1 Carrot Wastes as Livestock Feeds

Carrots are highly delicious to cattle and are readily eaten. For lactating dairy cows, carrots provide a good source of ME (3.29 Mcal/kg DM) and NE (1.94 Mcal/kg DM) (NRC 1989). Dairy cows and young bulls can be given up to 20 and 25 kg of fresh carrots per day, respectively (Morel d'Arleux 1990), and steers can have up to 40% of their diet made up of fresh carrots with no negative consequences (Rust and Buskirk 2008). Incorporating cull carrots at high levels in animal feeds can cause off-colored fat in finishing lambs and cattle. Thus, finishing diets should be kept to 20% or less (Lardy and Anderson 2009). Fresh carrots should be supplemented with fibrous feeds to prevent acidity and scouring and should be introduced gradually into the diet due to their high fermentable sugar content (8–10 days). Carrots in ration of dairy cows for a long time boosted the carotene level of their milk, resulting in yellow-colored milk fat (Fuller 2004). Fresh carrots can be given to goats at a rate of 2–4 kg per day (Morel d'Arleux 1990). Carrot waste in dried form could be added up to 50% in growing rabbit rations instead of the most common ingredients employed in this study, with no negative impacts on productivity, nutrient digestibility, blood components, or cost-effectiveness (El-Medany et al. 2008). The use of 50% carrot top hay in the berseem hay diet of Rahmani sheep improved nutritional digestion (Bassiouni et al. 1999). For lactating dairy cows, carrots provide a good source of ME (3.29 Mcal/kg DM) and NE (1.94 Mcal/kg DM).

4.7 Pea Wastes

Pea, along with soybean, groundnut, and beans, is one of the four most significant legume crops. The pea straw left to dry in the field after harvesting sweet or garden peas contains 5–10% crude protein, the neutral detergent fiber content of 53–63%, and a mineral content of 7–12%, especially calcium (Leclerc 2003). The digestion kinetic characteristics for fresh pea vine dry matter showed that it has a degradable fraction (60.8%), with effective degradability (52.3%) and true degradability (75.1%). These have a high rumen fill value, which means they have poor dry matter intake potential.

4.7.1 Pea Wastes as Livestock Feeds

Small ruminants consume more pea straw as a percentage of body weight than large ruminants (Singh et al. 1994). Pea straw has more nutritional value than cereal straws due to their higher protein content and lower fiber level. It is between cereal straw and grass hay in terms of quality, and horses can eat up to 3–4 kg per day (Leclerc 2003). For lactating dairy cows, the ensiled pea vines included 13% crude protein and 3.3% ether extract with 2.09 Mcal ME/kg DM and 1.28 Mcal NE/kg DM (NRC 1989). The pea vines have comparable nutritional content with clover for rabbits (Zaza et al. 2009). Pea wastes are fed to animals as silage. They are reported to supply vital proteins and starch to fulfill and store energy reserves in livestock over extended periods (Rondahl et al. 2011).

4.8 Baby Corn Wastes

The cost of cultivation of baby corn is low, and the area under production in India has expanded significantly. Only 15% of this baby corn cob is edible, while the other 85% is made of outer cover with a structure like silky thread known as baby corn husk with silk. The average yield of baby corn in India is 7.5–8.7 tonnes per hectare. The by-products/wastes derived from baby corn include stalks and leaves after harvesting ears (30 tonnes/ha), 5.56 tonnes/ha husk and silk, and 3.13 tonnes/ha male buds (Anonymous 2006).

4.8.1 Baby Corn Wastes as Livestock Feeds

The crude protein content in the husk of fresh baby corn is 11.7%, and the ether extract content is 1.8%. The residual plant is harvested for use as livestock feed after 3–4 baby corn harvest. The dry matter intake (DMI) of baby corn husk in sheep was 2.7% of body weight (BW) when the material was dry, while it was 1.6% and 1.2%

of BW in fresh and ensiled forms, respectively (Cheva-Isarakul 1990). Bakshi and Wadhwa (2012a) tested fresh chaffed baby corn husk, baby corn husk wilted for 2–3 days and ensiled for 42 days, and fresh baby corn husk combined with chaffed rice straw in a 70:30 ratio and ensiled for 42 days as animal feed. The fodder production of baby corn varieties was lower than that of traditional maize fodder varieties, but the chemical content was equivalent to conventional maize fodder types.

4.9 Bottle Gourd Wastes

The vegetable bottle gourd is widely utilized as feed. Moreover, bottled gourd juice is thought to have medicinal characteristics. It has been used to treat urinary disorders, epilepsy, insanity, other nerve ailments, acidity in the stomach, ulcers and indigestion, flatulence, and even piles (Prajapati et al. 2010; Sharma et al. 2012; Rahman 2003). Bottle gourd pulp is leftover after the juice has been extracted. It contains a high percentage of protein (24.3%) and cell wall components in a lower concentration.

4.9.1 Bottle Gourd Wastes as Livestock Feeds

Sun drying the bottle gourd pulp and then grinding it for animal feed can help to preserve it. Wadhwa et al. (2013) found that bottle gourd waste may be added up to 50% into adult ruminant concentrate mixtures. The in vivo studies on bucks which were given bottle gourd diet of 0, 25, and 50% in iso-nitrogenous and iso-caloric concentrate mixtures with the addition of green fodder (50:50) showed increased fungal growth in the rumen while decreasing population of bacteria and protozoan with an increasing amount of bottle gourd in the diet. The daily dry matter intake, on the other hand, was unaffected. Crude protein digestibility was reduced; however, acid detergent fiber and cellulose digestibility were improved, with no effect on nitrogen retention in bucks (Wadhwa and Bakshi 2013).

4.10 Other Vegetables

Water spinach (*Ipomoea* sp.) produces a lot of biomass output and rich crude protein content (280 g/kg dry matter) with a low crude fiber content (120 g/kg dry matter) and has proven to be a beneficial basal diet for rabbits (Luyen 2003; Ho Bunyeth 2003; Phimmmasan et al. 2004). On the other hand, onion wastes are often not acceptable as fodder due to their firm, pungent scent, and sensitivity to phytopathogens. The tops, scales, and outer fleshy leaves with bottom bulbs are the main by-products of onion bulb peeling industries. The by-products from agro-processing sectors account for around 10% of onion waste (Wadhwa and Bakshi 2013). If given to ruminants at high levels, cull onions can develop anemia due to sulfur compounds that can cause hemolysis of red blood cells (Lardy and Anderson 2009). Non-lactating dairy cows fed 20 kg onions (0.04 kg/kg body weight) with 10 kg maize silage and straw ad libitum developed onion toxicity. Within 24 h, signs of poisoning such as tachycardia, appetence, tachypnoea, sluggishness, staggering, decreased rumen motility, and jaundiced conjunctivae were observed (Van Der Kolk 2000). Snow peas have edible pods and are delicate in flavor, which makes them suitable for feed material. Snow peas that have been harmed by frost rejected quality and are not exported. Cull snow peas comprise 23–25% crude protein, 1.0% ether extract, and 35.8% total sugars on a dry matter basis. They are also abundant in vitamins such as vitamins A, B complex, C, and K and pigments that help vision, such as zeaxanthin and lutein. The sun-dried snow peas can replace 50% of iso-nitrogenous and 100% of iso-caloric concentrate mixture, respectively, in the ration of male buffalo calves (168 kg body weight). The snow peas that are fresh or sun-dried are highly consumable and may be used effectively in livestock diets without affecting nutrient utilization or animal health (Bakshi and Wadhwa 2012b).

5 Conclusion and Future Perspectives

This overview demonstrates the value of FVWs as a good supplement of phytochemicals and nutrients for ruminants, besides lowering feed production costs. Animal diets must be less expensive than traditional feedstuffs and, at the same time, must provide sufficient nutrients required for the growth and development of livestock. Processing methods and instruments used can have varying impacts on the chemical contents of by-products. Some waste products have a little nutritional value as feedstuffs; however, their usage can be improved by heating, drying, grinding, steaming, pelleting, radiation, chemical treatment, fermentation, etc. These processes add feed value as well as impart additional nutrient elements to feed. For example, the grinding process can prevent a micro-mineral shortage by adding metals to the feeds from the grinding machines. Iron, zinc, copper, manganese, and sodium are the metals that are added to the feed. For example, mangoes can replace conventional fodder (maize bran), pineapple wastes provide appropriate roughage, citrus peels and seeds are abundant in antioxidants, and citrus pulp in dried form can be used as a replacement for grain. The baby corn fodder has high digestibility comparable to maize fodder. At the same time, other vegetables like tomato, carrot, pumpkin, beetroot, etc. are rich in phytochemicals that complement the nutrient requirement of livestock.

Lycopene, phenols, and β-carotene are likely the major antioxidants present in fruit and vegetable wastes which possess certain health benefits. The establishment of small-scale feed manufacturing operations near sources of FVWs could be an enticing choice for their cost-effective, efficient use and management. However, before FVWs are processed into animal feeds, regular monitoring of potentially hazardous substances should be recommended. The Office International des Epizooties has developed best practices and safety guidelines for converting agricultural wastes to animal feed, presently World Organization for Animal Health in Paris. In India, Food Safety and Standards Authority of India (FSSAI) decided to put commercial feeds/feed materials (i.e., compound cattle feed) intended for meat and dairy-producing animals within the Food Safety and Standards Act, 2006, and issued a directive that animal feed for food-producing animals must meet Bureau of Indian Standards requirements. This could be beneficial in determining the dangers related to the presence of pollutants in the ration of animals, meat for export, and in developing quality feeds of a high standard. Livestock feed production is the best economical approach to eliminating fruit and vegetable wastes that pose a big problem for their disposal, causing environmental hazards.

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Chapter 7
Vegetable and Fruit Wastes as Substrate for Production of Single-Cell Protein and Aquafeed Meal

Fataneh Hashempour-Baltork, Parastou Farshi, and Kianoush Khosravi-Darani

Abstract Agricultural residues, including fruit and vegetable residues, which usually contain starch or cellulose, are used for bioconversion into value-added products. Bioconversion provides several advantages, such as high value considering their material and energy recovery, decrease in landfill areas, lower cost of the technology, and the farmers' income. Bioprocessing is of great importance for horticultural waste management to satisfy the needs of developing countries. Fermentation (solid-state and submerged) is considered an important tool to increase the nutritional value (providing more proteins, amino acids, and other biomolecules) of SCP and aquafeed meal ingredients. This chapter investigates the role of fruit and vegetable wastes in the production of single-cell protein (SCP) and aquafeed meal.

Keywords Fruit and vegetable wastes · Single-cell protein · Aquafeed meal · Economics · Eco-friendly process · Yeast · Bacteria · Algae

1 Introduction

Due to the growing population in the world and the need for effective agriculture practices to provide food for people, the types and volume of agricultural waste biomass are increasing. Each year, 140 billion metric tons of biomass is produced globally from agriculture by-products (Singhania et al. 2017). Community-level farms and large-scale industries favor these biomass wastes for developing high-value products (Panda et al. 2018).

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The improper management of agricultural waste will result in rotten biomass, which would generate leachate and methane. Moreover, the open burning of these wastes by farmers to clean the lands would emit other pollutants and CO_2, which contribute to local air, water, and soil pollution (Singhania et al. 2017). Agricultural residues, including those from fruits and vegetables, usually contain starch or cellulose, and few of them are rich in nitrogen. Therefore, the wastes containing starch and cellulose are being used for bioconversion.

Utilizing biomass in the mentioned ways provides several advantages, such as high value considering their material and energy recovery, decrease in landfill areas, and erosion control. In addition, they add to the farmers' income. Moreover, the development of waste recycling technologies results in the extraction of high value-added products such as single-cell oil (Finco et al. 2017), enzymes (El-Bakry et al. 2015), aquafeed meal (Rajesh and Raj 2010), and single-cell protein (SCP) (Panda et al. 2018; Hashempour-Baltork et al. 2020a, b).

SCPs are considered dietary single-cell microorganisms in that their protein extracts or biomass are derived from a mixed or pure microscopic fungus, yeasts, algae, or bacterial cultures. SCP does not have any adverse effects such as greenhouse gas releases, climate changes, pollution of freshwater resources, or degradation of lands. However, the substrate of SCP, which is needed to be food-grade and should include carbohydrates and necessary compounds for microbial growth, has a substantial effect on its cost-benefit (Hosseini et al. 2009). There are numerous studies on the production of SCP from several waste materials such as grass silage fiber (Pihlajaniemi et al. 2020), cactus peer biomass (Nancib et al. 1997), industrial pea processing by-product (Souza Filho et al. 2018), sugar wastes (Saejung and Salasook 2020), oil (Juszczyk et al. 2019), potato waste (Spiller et al. 2019), and date fruit wastes (Hashempour-Baltork et al. 2020a, b).

Another issue that is addressed in this chapter is related to aquaculture. Recently, aquaculture has gotten worldwide attention due to the progressing fish production industry, which is decreasing due to the reduced output from capture fishery (FAO 2009). One major issue facing fish production is balancing the rapid growth of fish and optimum use of the supplied feed (Ajani et al. 2011). The aquaculture growth has been rapid during the last 50 years, which has been increased by around 10% per year in the previous decade. As a result, there is an increasing interest in developing cost-effective fish meal alternatives using plant- and animal-based protein sources (Dawodu et al. 2012). Although the fish meal is a substantial source of protein, it is very costly. Therefore, producers of fish are looking for alternative raw materials to be used as cost-effective protein sources. High global availability of plant ingredients at reasonable prices, and specific nutritional properties of them which are comparable to fish meal, makes them be considered as suitable substitutes. In this chapter, we focus on the role of agricultural waste in the production of SCP and aquafeed meal primarily through solid-state and, to a less extent, submerged fermentation.

2 Solid-State and Submerged Fermentation

The SCP and aquafeed meal can be produced using different fermentation methods and cultivation of particular microorganisms from fungi, yeasts, bacteria, and algae in appropriate media.

2.1 Solid-State Fermentation (SSF)

Solid-state processes involve growing the organisms on a substrate that is primarily insoluble such that there is essentially no free liquid (Bhargav et al. 2008). Advantages of SSF include simplicity of the fermentation operation, the high capacity of the microbes to release concentrated enzymes during growth for substrate hydrolysis, the substrate penetrating capacity of fungal mycelium, and the competitive advantage fungi hold over bacteria in the low water-activity environment (Londoño-Hernandez et al. 2020). SSF processes have been used for protein enrichment and improvement of digestibility of food industry solid wastes using substrates which include the following: filter-pressed cakes, for example, from vegetable oil recovery; fruit and vegetable skins; unripe and decomposing fruits and vegetables; grape marc; root crop wastes such as beet, cassava, and sweet potato; and fruit and coconut pulps (Ward et al. 2006).

2.2 Submerged Fermentation

Submerged fermentation involves inoculation of the microbial culture into the liquid medium to produce the desired product. Most commercial products are produced through the submerged fermentation processes (Subramaniyam and Vimala 2012). Examples of liquid wastes suitable for protein enrichment include food processing effluents; processing filtrates and decantation liquid wastes; fruit and vegetable waste hydrolysates; plant oil effluents; cannery effluents; pulp and peel extracts; waste coconut milk; ethanol grain, fruit, and sugar cane (vinasse) stillages; various pre-treated hydrolyzed bagasse; and other hydrolyzed cellulose wastes (Ward et al. 2006).

3 Vegetable and Fruit Wastes in SCP Production

The nonedible portions of vegetables and fruits are pods, skins, rinds, nuts, seeds, peels, stone (mango, jackfruits, litchi), etc. These account for about 10–50% of the total weight of the fresh produce. These wastes can be processed into SCP and aquafeed meals.

3.1 Single-Cell Protein (SCP)

SCP refers to protein derived from cells of microorganisms such as yeast, fungi, algae, and bacteria, which are grown on various carbon sources for synthesis. In general, in 100 g of dry matter, SCP contains 45 g proteins, 25 g fibers, 13 g fats, 10 g carbohydrates, and several vitamins and minerals (Finnigan et al. 2017). Moreover, toxicology studies have proven that SCP does not have adverse effects on the normal growth of animals and human beings and short- or long-term SCP consumption does not cause any general health concerns (Finnigan et al. 2017). Furthermore, the positive impacts of the consumption of fungal protein on low-density lipoprotein and high-density lipoprotein cholesterols, total blood cholesterol, reducing the food-borne pathogens, glycemic response, and satiety were reported (Hashempour-Baltork et al. 2020a, b). Moreover, the protein digestibility corrected amino acid (Spiller et al. 2019) score of SCP is about 1.0. Fiber content did not indicate any adverse effect on mineral absorption. However, some reports show the intolerance of individuals to SCP, but the level of intolerance is lower than that of egg and soya (Finnigan et al. 2017).

Two strategies, such as reducing overall feed or disposal costs and diminishing the pollution from wastes, are important in the fermentation of horticultural wastes to protein-rich feed. Vegetable and fruit processing, confectionery, starch industries, the alcoholic beverage sector (wineries, breweries, and distilleries), the vegetable oil industries, and other plant-based industries such as coffee, cocoa, and tea processing are examples of waste sources for SCP production.

Most food and agro-industrial wastes and by-products are not good sources of nutrients. Thus, they are not appropriate for non-ruminant animals. However, a possible solution can be achieved in such conditions by utilizing microorganisms to produce products with higher nutritional value (higher vitamin and protein contents) and increased digestibility from agro-industrial wastes (Rajesh and Raj 2010). Bacteria, fungi, and yeasts are the main organisms in protein enrichment of horticultural wastes by converting some of the carbon-rich fractions of the wastes into microbial protein (Hosseini et al. 2009; Pradeep and Pradeep 2013; Reihani and Khosravi-Darani 2018, 2019). A few studies have been conducted on SCP production by submerged fermentation considering its advantages, such as better mass-heat transfer, reproducible properties, and culture homogeneity, compared to solid-state fermentation (SSF) (Fazenda et al. 2008; Pradeep and Pradeep 2013).

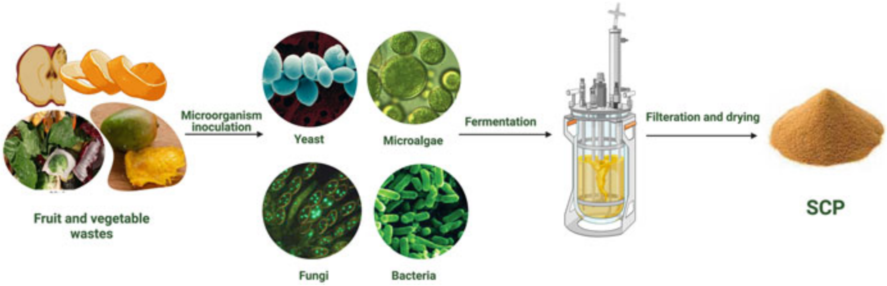

Fig. 7.1 Process of single-cell protein production by fruit and vegetable waste

The SCP production process from FVWs is shown in Fig. 7.1.

3.1.1 Fungi

Many fungal species such as *Pleurotus florida*, *Aspergillus (A.) niger*, and *Fusarium (F.) venenatum* are used for SCP production. Still, some of them with higher protein content are preferred (Ravinder et al. 2003). Ascomycetes such as *Monascus* spp., *F. venenatum*, and *Neurospora* spp. are generally considered safe microorganisms (Ferreira et al. 2016). Fungi that are particularly used for the production of SCP consist up to 63% protein. Moreover, their amino acid profiles are according to the FAO's standard regarding protein and amino acids in human nutrition (Nasseri et al. 2011). Fungal proteins are good sources of threonine and lysine; however, they are low in the amino acids containing sulfur, such as methionine and cysteine (Nasseri et al. 2011). In addition, the SCP produced from fungi includes vitamins and some other bioactive compounds such as thiamine, niacin, riboflavin, biotin, folic acid, aminobenzoic acid, pyridoxine, choline, glutathione, pantothenic acid, and streptogramin. Moreover, fungi contain high nucleic acid content (up to 10%) in comparison to algae (up to 6%) (Nangul and Bhatia 2021).

Citrus fruit wastes have been used in a variety of protein enrichment SCP processes. For example, lemon and grapefruit pulps were incubated separately with *Penicillium (P.) roqueforti* and *A. niger* in SSF. As a result, the crude protein content in lemon pulp reached 20.1 and 17.9% in *A. niger* and *P. roqueforti*, respectively. Corresponding values in grapefruit pulp were 24.1% and 21.2%, respectively (Deveci and Ozyurt 2005). Also, a five-fold increase in protein content of the substrate was achieved by *Sporotrichum pulverulentum* and *A. niger* in submerged culture using citrus waste as the carbon source (Suha Sukan and Yasin 1986).

The protein content of banana wastes was raised from 6% to 18% by using a strain of *A. niger* in SSF. As the substrate consumption was 24% of initial weight after 43 h of fermentation, protein production was calculated to be 150% of the initial content. The SCP produced from banana waste had the following compositions: total sugars (50%), reducing sugars (13%), and proteins (18%) (Baldensperger et al.

Table 7.1 Fruit/vegetable waste as substrate in single-cell protein production by fungi

Fungus	Substrate	Protein content (%w/w)	Reference
Zygosaccharomyces rouxii, *Hanseniaspora uvarum*,	Spoiled date palm fruits	48.9	Hashem et al. (2014)
Fusarium venenatum	Date extract	33	Prakash et al. (2015)
Fusarium venenatum	Date extract, jaggery water	–	Prakash et al. (2014)
Aspergillus niger	Apple pomace	17–20	Bhalla and Joshi (1994)
A. niger	Banana waste	18	Baldensperger et al. (1985)
A. niger	Citrus pulp	25.6	De Gregorio et al. (2002)
A. niger	Waste liquor	50	Chiou et al. (2001)
Trichoderma viride	Citrus pulp	32	De Gregorio et al. (2002)

1985). Therefore, the fermented banana waste can be considered suitable for use as fish feed.

Many studies were conducted to formulate a fermentation medium to convert the waste peels to reducing sugars and enrich the peels with microbial protein. Amylase-producing microorganisms, including *A. fumigatus*, *A. flavus*, *A. niger*, and *Pseudomonas* sp., were isolated from rotten cassava tuber discs. The highest protein yields were obtained with *A. fumigatus* followed by *A. niger* (Ray and Ward 2006).

A study was conducted on sweet potato roots and flour using strains of four species of *A. niger*, *Rhizopus stolonifer*, *Neurospora sitophila*, and *Saccharomyces cerevisiae* by SSF at 30 °C for 72 h. As a result, the protein content of the samples increased from 2.34 in the non-fermented roots to 11.50–12.62 in the fermented roots and 6.26 in the non-fermented flour to 7.83–9.70 in the fermented flour (Onifade et al. 2004).

Fungi have a significant role in fiber saccharification from various sources such as corns and pea. Thus, they are considered the main microbial protein producers (Matassa et al. 2016). Mycelia yield varies greatly depending on substrates and organisms. Fungal species are being used in SCP technology for bioconversion of lignocellulosic wastes. The carbon source for most of the filamentous fungal species is fruit wastes (Hosseini and Khosravi-Darani 2011), such as date waste for *A. oryzae*, *F. graminearum*, and *F. venenatum* and lemon pulp for *A. niger* (Hashempour-Baltork et al. 2020a, b; Prakash et al. 2014). Table 7.1 provides reports from researchers on using different substrates for SCP production by fungi.

3.1.2 Yeasts

Yeasts have excellent nutritional quality; thus, they have been used as a good source of SCP production for a long time. However, compared to the protein content of bacteria (80%), yeasts have lower protein content (65%) and a low growth rate (Nasseri et al. 2011). High nucleic acid content and low cell wall digestibility are two principal limiting factors for yeast (Nasseri et al. 2011).

Studies conducted by Aggelopoulos et al. (2014) on the growth of kefir, *S. cerevisiae*, and *Kluyveromyces marxianus* by SSF method using different substrates consisting of food industry wastes such as molasses, potato, and orange bagasse, whey, and solid waste from the brewery showed a protein content of 23% in kefir, 39% in *S. cerevisiae*, and 34% in *K. marxianus* (Aggelopoulos et al. 2014). Furthermore, Gao et al. (2012) has developed a successful bioprocess for SCP production by *Candida tropicalis* using soy molasses. This SCP consisted of 5.28% nucleic acids and 56.42% crude protein. These results showed that *C. tropicalis* is a good source for SCP production, using a low-cost substrate such as soy molasses (Gao et al. 2012). *Candida*, *Yarrowia*, *Rhodotorula*, *Cryptococcus*, *Rhodosporidium*, *Lipomyces*, and *Trichosporon* are typical SCP-producing yeasts.

There were studies evaluating orange and cucumber peels for the SCP production by *S. cerevisiae* using submerged fermentation (Mondal et al. 2012). Fruit waste and cheese whey are being used as carbon sources for most yeast species. For example, date waste was used to produce SCP from *Thermomyces lanuginosus* and *Trichoderma reesei* (Mondal et al. 2012). Other fruit wastes such as apple waste, pomegranate rind, beet pulp, orange plantain, banana skin, sweet orange peel, Belles' fruit peels, cactus pear, pineapple waste, virgin grape marc, and mango waste were used as substrates for *Candida utilis*, *C. tropicalis*, and *S. cerevisiae* (Reihani and Khosravi-Darani 2019).

Literature survey revealed that fermentation of *S. cerevisiae* on sweet orange (*Citrus sinensis*) residue led to an increase in protein content. In a 4% (w/w) citrus waste medium at 36 °C by 12 h incubation period, the biomass product containing 57% (w/w) crude protein was produced (Nwabueze and Oguntimein 1987). *Trichoderma viride* and *Geotrichum candidum* on the orange peel in submerged fermentation achieved 20% crude protein and total digestibility of 65% (Vaccarino et al. 1989). In contrast, a higher nutritional value (about 30% crude protein having 80% total digestibility) was achieved in SSF using the same fungi. However, it led to decreased productivity concerning time (Vaccarino et al. 1989).

Fermentation of banana liquid extract with *C. utilis* and *Lipomyces kononenkoae* resulted in an increase in dry biomass levels of up to 14.9 g/L with protein contents up to 47% (Horn et al. 1988). In addition, banana skins were fermented with *Saccharomyces uvarum* as a nitrogen source, leading to increased microbial cell mass, SCP enrichment, and cell crude protein content, 4.98, 0.89, and 2.90 g/L, respectively (Enwefa 1991).

On the other hand, vegetable plant extracts have also been used for SCP production. Three yeast species, *S. cerevisiae*, *Torula utilis*, and *Candida lipolytica*, were

Table 7.2 Fruit/vegetable waste as substrate in single-cell protein production by yeasts

Yeasts	Substrate	Protein content (%w/w)	Reference
Debaryomyces hansenii	Brewer's spent grain hemicellulosic hydrolysate	31.8	Duarte et al. (2007)
Candida utilis	Waste capsicum powder	48.2	Zhao et al. (2010)
Saccharomyces cerevisiae	Combined agricultural waste (mostly protein rich)	38.5	Aggelopoulos et al. (2014)
Kluyveromyces marxianus	Combined agricultural waste (mostly protein rich)	33.7	Aggelopoulos et al. (2014)
Kefir microorganisms	Combined agricultural waste (mostly protein rich)	23.6	Aggelopoulos et al. (2014)
S. cerevisiae	Molasses, orange pulp, brewer's spent grain	39	Aggelopoulos et al. (2014)
C. utilis	Potato starch industry waste	46	Liu et al. (2013)
C. utilis	Potato wastewater	49	Kurcz et al. (2018)
Hanseniaspora uvarum	Spoiled date palm fruit	49	Hashem et al. (2014)
Zygosaccharomyces rouxii	Spoiled date palm fruit	49	Hashem et al. (2014)

grown in the deproteinized leaf juices of four cruciferous plants: turnip, mustard, radish, and cauliflower (Chanda and Chakrabarti 1996). The results indicated the yeast biomass was rich in protein (45–54%) and B group vitamins. Yam peel extract was used as a substrate for SCP production using the fungus, *Botryodiplodia theobromae* (Aderiye and Akindolani 1988).

In the manufacture of starch from cassava, four types of wastes, including skin (peel), inner rinds, fibrous residues, and wastewater, constitute about 20–30% by weight of the cassava roots processed (Ray 2004; Sriroth et al. 2000). These wastes are suitable substrates for protein enrichment and SCP production by culturing microorganisms such as *S. cerevisiae* and *C. tropicalis* through SSF (Adeyemi and Sipe 2005). Cassava waste peels contain about 42% carbohydrate, 20.8% crude fiber, and 1% protein and thus may constitute up to 55% of the original tuber weight as substrates for SCP protein enrichment (Odunfa and Shasore 1987). Further, several yeast strains, i.e., *C. tropicalis*, *Schwanniomyces occidentalis*, *Torulopsis wickerham*, *Endomycopsis fibuligera*, *C. utilis*, and *Saccharomyces* spp., when applied individually or in co-culture resulted in protein enrichment. *C. tropicalis* gave the highest protein enrichment (Jamuna and Ramakrishna 1989).

Industrial wastes from the date palm, coconut palms, cassava, sweet potato, yams, mango, pineapple, and grapes were used for SCP production using *Yarrowia lipolytica*, *K. marxianus*, *Kluyveromyces lactis*, *S. cerevisiae*, *Clavaria versatilis*, *Mucor hiemalis*, *Torulopsis cremoris*, and *Kluyveromyces fragilis* (Reihani and Khosravi-Darani 2019). Table 7.2 shows the studies reported on the application of different substrates for the production of SCP by yeasts.

3.1.3 Algae

Microalgae, which are single-cell microorganisms, have autotrophic growth, in which they use carbon dioxide and light as carbon and energy suppliers. The microalgae use cellular biomass to produce up to 70% SCP by converting solar energy (Nasseri et al. 2011). Otherwise, in heterotrophic growth, manure, molasses, or other cost-effective organic materials such as industrial wastes are used as carbon sources (Robinson 2014).

Numerous raw materials are considered as cultivation media and are used in the production of SCP from microalgae. For example, tempeh waste, tofu waste, and cheese waste were used by *Chlorella*, resulting in total protein content of 52%, 52.32%, and 15.43%, respectively (Putri 2018). In addition, recent algal SCP research showed that *Chlorella* sp. and *Spirulina* provided the protein content, 52% and 56%, respectively (Sharif et al. 2021).

3.1.4 Bacteria

Bacterial SCP has high levels of nucleic acid, small cell size, low density, and 50–80% protein content (dry weight), and it can quickly multiply (within 20–120 min intervals) on a wide variety of substrates such as starches, sugar, wastes like petrochemicals (methanol and ethanol) or organic wastes, raw materials, and water resources with high content of minerals and nutrients (Table 7.3) (Øverland et al. 2010; Suman et al. 2015).

Table 7.3 shows that bacterial species such as *Escherichia coli*, *Haloarcula* sp., *Methylophilus methylotrophus*, and *Rhodopseudomonas palustris* are very effective in producing SCP, so they have been used a lot for protein production. For example, *Rhodobacter sphaeroides* Z08 has produced 52% SCP using soybean waste as a substrate (He et al. 2010). This is because the soya bean hull produced during soya bean oil extraction is a cost-effective feed ingredient containing high fiber.

A mixed batch culture of *Cellulomonas* sp. and *Bacillus (B.) subtilis* was grown using wastes from a factory producing potato crisps at 37 °C for 72 h (Rubio and Molina 1989). The highest protein content in the biomass was about 33.3% (dry weight), with a reduction of chemical oxygen demand. Thus, biomass with high protein content suitable for animal feed was produced.

Methylophilus used in animal feed has a generation time of around 2 h, and it produces a more appropriate protein composition than fungi or yeast. Thus, bacteria such as *Methylophilus methylotrophus*, *Brevibacterium*, *Acinetobacter calcoaceticus*, *B. megaterium*, *Achromobacter delvaevate*, *Aeromonas hydrophila*, *Methylomonas methylotrophus*, *Cellulomonas* sp., *B. subtilis*, *Rhodopseudomonas capsulate*, *Pseudomonas fluorescens*, *Thermomonospora fusca*, *Flavobacterium* sp., *and Lactobacillus* species can produce large quantities of SCP animal feed (Bratosin et al. 2021).

Table 7.3 Fruit/vegetable waste as substrate in single-cell protein production by bacteria

Bacteria	Substrate	Protein content (% w/w)	Reference
Bacillus licheniformis	Potato starch processing waste (cellulose rich)	38.2	Liu et al. (2014)
Mixed culture (*Bacillus pumilus*, *Candida utilis*, *Aspergillus niger)*	Potato starch processing waste (cellulose rich)	46.1	Liu et al. (2013)
Escherichia coli	Ram horn	66	Kurbanoglu and Algur (2002)
B. cereus	Ram horn	68	Kurbanoglu and Algur (2002)
B. subtilis	Ram horn	71	Kurbanoglu and Algur (2002)
B. stearothermophilus	Agricultural waste	79	Ugwuanyi (2008)
B. Licheniformis	Potato starch processing waste	38	Liu et al. (2014)
B. pumilus	Potato starch processing waste	46	Liu et al. (2013)
Rhizospheric diazotrophs	Brewery wastewater	55	Lee et al. (2015)
Rhodobacter sphaeroides P47	Pineapple waste	66.6	Noparatnaraporn and Nagai (1986)
Rhodopseudomonas palustris P1	Fermented pineapple extract	63	Kornochalert et al. (2014)
Rhodopseudomonas and R. fulvum	Sugar refinery wastewater	58	Balloni et al. (1987)
Rhodobacter sphaeroides P47	Dehydrated medium frompineapple peel waste	66.6	Noparatnaraporn and Nagai (1986)
Rhodocyclus gelatinosus	Cassava waste	56	Noparatnaraporn et al. (1987)

Molasses, ram horn hydrolysate, glucose, liquid whey, and beet pulp hydrolysates were used as carbon sources for bacteria such as *Escherichia coli*, *B. licheniformis*, *B. cereus*, *B. coagulans*, *B. subtilis*, *Brevibacterium lactofermentum*, and *B. stearothermophilus* (Reihani and Khosravi-Darani 2019). Table 7.3 provides studies on using different substrates for the production of SCP by bacteria.

4 Vegetable and Fruit Wastes in Aquafeed Meal Production

Fish meal is an extensively used animal protein source in the aquafeed industry due to its increased digestibility, palatability, and high nutritional value. However, the lack of resources and rising prices can seriously limit the use of fish meal in aquaculture. In fish farming activities, production cost has control over the productivity of fish farmers, in which the feed cost can account for up to 50–80% of the entire operational cost (Dhillon et al. 2013).

The fish diet consists of 40–56% protein, which is considered the principal compound in the commercial diet (Namulawa et al. 2013). Thus, there is a great interest to find the renewable supplies of protein sources to be used as alternatives to fish meal

Plant protein sources have limitations in the fish feed industry, such as their unbalanced amino acid profiles, low protein content and palatability, and anti-nutritional factor content. As it was mentioned, the nutritional value of proteins with plant and animal sources increases with fermentation. These protein sources can be treated with suitable microorganisms to maintain their nutrients to be included in aquafeed, which would result in reduced environmental pollution and feed costs and better nutritional value and nutrient efficiency. The fermentation process was effectively applied in poultry and livestock nutrition, which is based on microorganisms cultured under certain conditions (Sugiharto and Ranjitkar 2019). The microorganisms can reduce the aflatoxin risk in feed ingredients before feeding (Mwihia et al. 2018). Furthermore, these microorganisms can synergistically be beneficial for the gastrointestinal tract (Yamamoto et al. 2010) organisms causing an increase in the feed digestibility of aquatic animals, in addition to their role as probiotics (Yamamoto et al. 2010) (Xie et al. 2016). Therefore, aquatic animals can increase growth performance, feed efficiency, immunity, and tolerance to different farming stressors (Jannathulla et al. 2019).

Many kinds of agricultural wastes rich in fermented fibers such as rice husk, corncob, apple pomace, and papaya processing waste were used in shrimp or fish feed additives (Dhillon et al. 2013; Kang et al. 2010). Different fungi were indicated to have either cellulolytic or amylolytic activities. Therefore, they can be used for the fermentation of carbohydrate-rich wastes. After fermentation, they can supply the required protein sources for the feed component.

Al Azad and Lal (2018) investigated on nutritional status of the leafy vegetable waste bio-converted product as an aquaculture feed supplement. Proximate compositions of bio-converted leafy vegetable wastes were improved after 6 days with 30% inoculums of *Afifella marina* strain M.E. (KC205142). However, during the feeding trial in Tilapia (*Oreochromis niloticus*), no significant differences were observed in the feed intake (g/fish/day). Still, significant differences were observed in the value of feed conversion ratio and weight gain (%) among the used diets (Al Azad and Lal 2018).

Some fungi such as *Rhizopus oligosporus*, *A. niger*, *S. cerevisiae*, and *C. utilis* could increase the protein content of biomass throughout fermentation (Dhillon et al. 2013). The mold group consisting *Trichoderma reesei*, *T. viride*, *A. oryzae*, and *Rhizopus oligosporus* were shown to use corncob in the feed formulation of *Java barb* fish. They were demonstrated to increase the growth of this fish (Rostika and Safitri 2012). Yeast protein is easily digestible and is widely being used for shrimp and fish feed supplements. However, despite its application as a protein source, it can improve the immune system and stimulate bacterial disease resistance (Kang et al. 2010). For instance, it is shown that the protein content of apple pomace increased after fermentation by *Gongronella butleri*, which resulted in a 44% increase in fish body mass (Vendruscolo et al. 2009). Table 7.4 provides studies on using different substrates for the production of an aquafeed meal.

5 Economic Aspects

Almost one-third of all plant-based food that is being produced for human consumption is lost or wasted. Significant steps have been taken to quantify food wastage volumes and their environmental effects (Gustavsson 2011; Kummu 2012). This work has shown that the actual wasted food has a monetary value of 936 billion USD. However, this does not comprise the social and environmental costs of the wastage produced in large amounts by society. Furthermore, there is a lack of understanding about costs of plant wastage, until now. Thus, letting the food be rotten may seem more profitable than processing them to reduce waste at both post-harvest and distribution stages. However, observing the benefits of plant wastage can help develop proper investments methods and policies.

SCP production can be profitable if specific strategies can be used for its economic production. The costs that are needed to be considered are the cost of raw materials, chemicals, or enzymes, the fermentation process scaling-up cost, and the cost of reducing agents for obligate anaerobes. The scale-up cost is directly exposed in the final product cost (Tesfaw and Assefa 2014). Therefore, continuous fermentation, which is the most profitable process, is preferred for industrial SCP production. In a study by Junaid et al. (2020), the capital investment, the cost of the product, and the obtained profit from the product were used to determine the economic fragility of SCP production. This goal can be achieved through advanced down-streaming methods, improved fermentation methods, and microorganism strains.

An economic analysis conducted by Liu et al. (2014) showed that potato waste processing could simplify or solve issues such as pollution problems in the starch industry and the protein shortage required for animal feed in China (Liu et al. 2014). SCP can substitute soybean meal and other protein sources used in animal feed, such as fish and meat meal. However, offsets generated from these sources can cause various economic and environmental incentives (Hashempour-Baltork et al. 2020a, b).

Generally, the primary considerations for selecting the most appropriate waste product for SCP production are (1) availability of the specific waste product, (2) the transportation costs of the waste product, (3) waste product's pretreatment costs before its use in fermentation, and (4) concentrations of SCP after fermentation (in the final microbial biomass). This is because SCP microorganisms can incorporate most of the nutrients fed to them into the final biomass (Sharif et al. 2021).

Table 7.4 Fruit/vegetable waste as substrate in aquafeed meal production

Microorganism	Substrate	Aquatic animal	Result	Reference
Aspergillus niger	Waste of cabbage, cauliflower, banana peel, banana, potato, carrot, beet root, ladies' finger, peas,beans, capsicum	–	Increasein crude protein and amino acids, reduction in crude fat and crude fiber content	Rajesh and Raj (2010)
Saccharomyces cerevisiae Y1536 *and Rhizopus oryzae* FNCC 6157	Banana peels		Increase of protein content and decrease offiber content	Fatmawati et al. (2018)
Bacillus pumilus and *Pediococcus pentosaceus*	Duckweed(*Lemna* sp.)	Pacific white shrimp (*Litopenaeusvannamei*)	Duckweed can substitute up to 35% of fermented F.M. with and without negative effect on the growth and survivalperformance of cultured shrimp	del Carmen Flores-Miranda et al. (2015)
Lactobacillus spp.*Lb. acidophilus*, *Lb. kefiri*, *and Lb. sporogenes*	Lupin (*Lupinusangustifolius*)	Barramundi (*Latescalcarifer*)	Lupin's nutritional quality was improved by the fermentation by lactobacilli which allows its higher inclusion inbarramundi diets	Van Vo et al. (2015)
S. cerevisiae	Coconut waste	Catfish (*Clarias* sp.)	By including 20% of fermented coconut waste in the diet of *Clarias* sp., the growth of catfish can be increased	Farizaldi and Jafrinur (2017)
Saccharomyces boulardii, *S. cerevisiae* (MTCC 170), and lactic acid bacteria, viz.,*Lb. acidophilus* and *Lactoplantibacillus plantarum*	Mango peel and mango seedwaste	–	Enhancement of protein (13.01%) over the control (7.81%). Increase in fat ash and minerals Ca, Mg, K, Fe, and Mn	Munishamanna et al. (2017)
Bacterial protein	Agricultural raw material	African catfish (*Clarias gariepinus*)	Bacterial proteincan replace fishmeal wholly or partly in African catfish (*Clarias gariepinus*) diet, without compromising growth performance, haemato-biochemistry, intestinal integrity, or liver functionality	Adeoye et al. (2021)

6 Conclusion and Future Prospects

Nowadays, people should be aware of the consequences of the direct burning of agricultural waste on the farmlands and the potential application of these wastes as renewable natural resources for bioconversion into energy, which can benefit humans rather than have adverse effects on the environment. Thus, eco-friendly technologies are needed to protect our earth, and biotechnology has an important role in this objective. However, it needs global efforts.

An increase in the world population and the need for nutritional foods cause an increase in cereal and meat production. In recent decades, fertilizers, antibiotics, and pesticides have been used in forage production to meet the fodder requirement of meat animals. However, these chemicals cause environmental pollution and the development of bacteria resistant to antibiotics. Livestock can have an adverse effect on climate changes and greenhouse gas emissions, pollute freshwater resources, degrade lands, and increase reactive nitrogen or oxygen species, which are considered serious threats to natural biodiversity. SCP as a substitute for nutritional supplements can decrease the food shortage issues in fast-growing populations, especially in developing countries such as Iran. There is also a need for thoroughly reviewing and comparing different industrial wastes and their potential application as substrates for SCP production.

Fermentation is considered a fundamental tool to increase the nutritional value (more amino acids and other biomolecules) of non-conventional and conventional aquafeed ingredients. The addition of fermented feedstuff in aquafeed leads to improvements in immune response, growth performance, resistance to environmental stressors, oxidative status, and inhibition of infectious diseases of gut microbiota and bacterial quorum sensing, which determines aquatic animals' health and well-being. To ensure a profitable commercial aquaculture activity, local fermented feed ingredients can reduce feed costs, specifically in developing countries. However, the fermentation methods for aquafeed preparation require further studies, and more efforts are needed to show how fermented feed components can affect the aquatic animals' gastrointestinal tract microbiota. Recently, due to the higher requirement for fish feed, there has been a significantly increased interest in aquafeed. High-quality aquafeed is needed to be produced to satisfy the physiological needs of aquatic animals. Thus, the next generation aquafeed should have better quality to ensure improved health and superior growth. Therefore, thorough research is needed to explore other untapped applications and broader roles of fermented aquafeed in aquatic animal feed and health.

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Chapter 8
Composting and Vermicomposting Process: Relationship Between Microorganism and Physicochemical Parameters with Special Reference to Tropical Tuber Crops

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Abstract Composting and vermicomposting are techniques used to decompose organic residues, essentially used in soil for agricultural production. Composting is the natural process of recycling organic matter such as leaves and food scraps into a beneficial fertilizer that can benefit both soil and plants. Cultivating earthworms to convert organic waste into fertilizer is called vermicomposting or vermiculture. The converted end product or manure is called vermicompost. This compost will be rich in nitrogen, phosphorus, and potassium compared to other composts. Furthermore, compost and vermicompost are excellent nutrient-rich organic fertilizers and soil conditioners since they contain water-soluble compounds. As a result, it is popular in organic farming. This chapter discusses the composting and vermicomposting process regarding tropical tuber crops.

Keywords Composting · Vermicomposting · Organic waste · Earthworm · Nutrients · Soil fertility · Tuber crops

1 Introduction

Composting has been increasingly popular in agriculture in recent decades as public awareness of the environmental impact of synthetic agricultural inputs has increased. Composting has been linked to improvements in the physical and chemical qualities of soil. For millennia, organic waste has been used as a source of fertility. Decomposed manures and composted organic waste were widely used by ancient civilizations in the Mediterranean region, India, China, and Japan (Howard 1943; Epstein 1997). Fertilizer remains a primary source of fertility for many small farmers in underdeveloped countries, where its usage is limited by high costs and scarcity

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(Diop 1999; Pretty 2002). Humans have long recognized the earthworm's (Lumbricidae) ability to transform organic waste into humus-rich material with soil fertilizing properties. Earthworms were once referred to as the "intestines of the earth" by Aristotle (Kale 1993).

Global waste generation is expected to reach 27 billion tons per year by 2050. Asian continent currently produces one-third of the world's waste, with China (0–0.49) kg/capita/day and India (0.50–0.9) kg/capita/day contributing significantly (Kaza et al. 2018; Modak 2011). Globally, 292.4 million tons of municipal solid waste composted were produced. This included 22.3 million tons of yard trimmings (an increase of more than fivefold since 1990) and 2.6 million tons of food waste (4.1% of generation of wasted food). In addition, animal feed, co-digestion/anaerobic digestion, bio-based products/biochemical processing, land application, and sewerage/wastewater treatment managed 17.7 million tons of food (28.1% of lost food generation) in 2018.

If properly recycled, organic waste biomass can meet a portion of a crop's nutrient needs while also improving the soil's physical characteristics. Because soil-dwelling invertebrates of the phylum Annelida, Class Clitellata, and Order Oligochaeta account for more than 80% of soil invertebrate biomass. Because a significant portion (>60%) of organic waste is biodegradable, vermicomposting was seen as a boon not only for the reduction of organic pollution but also for the production of vermifertilizer (Senapati 1992). Although Charles Darwin, in the year 1881, wrote about the usefulness of earthworms in breaking down dead plant material, recycling nutrients, and turning over soil, the necessity for proper technology for recovering energy from non-conventional sources such as organic wastes was only recently understood. As a result, vermicompost has been regarded as a viable input for sustainable agriculture. It is rapidly gaining traction as a critical component of an integrated plant nutrition system (Purakayastha and Bhatnagar 2009).

2 Definition: Compost and Vermicompost

Composting is a biological process in which microorganisms decompose organic compounds under regulated circumstances. Vermicomposting, for example, is the process of using worms to transform organic waste into vermicompost, a humus-like material.

2.1 Compost

For generations, compost has been regarded as a helpful soil additive. It provides a stable organic matter source that enhances the physical, chemical, and biological aspects of soils, improving soil quality and crop yield. In addition, organic matter increases when compost is applied to the soil, which is good for soil health. Compost is made by allowing plant and animal leftovers to decompose biologically under supervised conditions (Eghball et al. 1997).

2.2 Vermicompost

Vermicomposting is a technique for composting various organic wastes using the gut microbes of surface-dwelling earthworms (Edwards and Lofty 1977). It is essentially a biological process of degradation of organic refuse brought about by the growth and activity of microorganisms and invertebrates, which form the so-called decomposer system. In decomposer entities, the earthworms constitute more than 80% of the invertebrate biomass and take the role of decomposition by stimulating microbial activity (Senapati and Dash 1984). Therefore, earthworms enhance the decomposition process by 25–40% (Dash and Senapati 1986) by ensuring an aerobic environment and increasing the surface area of litter available for the activity of microbes through fragmentation, feeding, and casting activity. Organics that are valuable for their bio-carbon are assimilated by the earthworms (Satchell 1983), and sludge cake could support earthworm growth without processing to compost.

2.3 Soil Microbial Populations and Plant Pathogen Suppression

Due to compost application in soil, the pathogen spores are covered by beneficial fungal and bacterial propagules; as a result, the activity of pathogen spores decreases. Beneficial populations frequently parasitize hyphae of pathogenic fungi.

Beneficial bacteria may inhibit pathogenic fungal spore germination by consuming amino acids, carbohydrates, volatile ethanol, and aldehydes generated from the root and seed tissue, as well as decaying plant waste. As a result, increasing the number of beneficial bacteria naturally present in compost or added into it can lead to a general reduction of plant pathogen biological control (Mazzola et al. 2002). Furthermore, rhizobacteria that promote plant growth may increase the incidence of disease-induced systemic resistance (Liu et al. 1995; Wei et al. 1996; Chen et al. 1995).

Vermicompost application can also minimize the level of soil pathogen. The worms' intestinal enzymes and the beneficial bacteria generated by worms compete for limited resources with pathogenic organisms (Eastman 1999). According to Satchell (1983), worms have been reported to exude fluids with antibacterial characteristics. In addition, pathogenic microorganisms are removed from worm castings due to nutritional competition between pathogenic organisms and indigenous microbiota (Eastman et al. 2001; Sidhu et al. 2001). According to Veena et al. (2013), the disease-suppression capability of vermicompost differed depending on the source. They also claimed that elephant foot yam treated with vermicompost/ vermiwash had a 10% taro leaf blight incidence and a 0–50% collar rot incidence.

A yield increase of 14–70% was noted in taro and elephant foot yam following vermicopost application (Veena et al. 2013). Furthermore, the root yield in the vermicompost applied orange flesh sweet potato field was comparable to the inorganic source of nutrient application, and its sustainable yield index was 0.92 with higher β-carotene (14.60 mg/100 g fresh tuber) content (Nedunchezhiyan et al. 2010). Therefore, there is an excellent scope for utilizing vermicompost for yield maximization, quality improvement, and eco-friendly management of diseases in tuber crops (Nedunchezhiyan et al. 2011).

2.4 Compost vs. Vermicompost

Compost is made by allowing plant and animal leftovers to decompose biologically under supervised conditions (Eghball et al. 1997). In the traditional composting process, initial temperature (10–40 °C) is maintained during which mesophilic microorganisms rapidly consume the labile organic matter. Then comes a stage where thermophilic microbes raise the temperature to 60 °C, consuming and breaking down lipids, proteins, and complex carbohydrates. Finally, the material cools down during the last step, allowing mesophilic organisms to recolonize and break down any residual resistant organic materials (Chefetz et al. 1996).

Researchers have been increasingly interested in adopting another biological process known as vermicompost, which is defined as "bio-oxidation and stabilization of organic material involving the joint action of earthworms and mesophilic microbes" (Aira et al. 2002). Vermicomposting is a method of composting that involves earthworms, which eat biomass and excrete it in digested form. This type of compost is known as vermicompost or wormicompost (Bansal and Kapoor 2000; Garg et al. 2006; Suthar 2009). It generates two valuable products: earthworm biomass and vermicompost (Sen and Chandra 2007). Vermicomposting is a basic biotechnological composting process in which certain earthworm species transform wastes into more helpful end products (Nagavallemma et al. 2004; Garg et al. 2005). Vermicomposting is the non-thermophilic biodegradation of organic matter by earthworms and microorganisms working together (Suthar 2009). According to Yadav and Garg (2011), earthworms act as mechanical blenders, modifying the biological, physical, and chemical status of organic matters by lowering the C/N ratio, increasing the surface area exposed to microorganisms, and making it more favorable for further decomposition. In some aspects, it varies from composting (Gandhi et al. 1997).

2.5 *Nutrient Profile of Compost and Vermicompost*

Farm compost has an average nutritional level of 0.5% N, 0.15% P_2O_5, and 0.5% K_2O. Superphosphate or rock phosphate, applied at a rate of 10 to 15 kg/t of raw material at the commencement of the composting process, can boost the nutrient value of farm compost. Compost made from municipal wastes such as night soil, street sweepings, and garbage has 1.4% nitrogen (N), 1.0% P_2O_5, and 1.4% potassium (K). However, the phosphorous (P) content in farm compost is low (0.4–0.8%). The addition of P balances the compost and provides nutrition to microorganisms, allowing them to multiply and decompose more quickly.

The amount of nutrients in vermicompost varies based on the waste sources utilized in the composting process. A wide range of nutrients is accessible in the compost if the waste components are heterogeneous. However, if the waste materials are homogeneous, just a few nutrients will be available. The following are some of the most typically found nutrients in vermicompost: organic carbon (C), 9.5–18.0%; N, 0.5–1.5%; P, 0.1–0.3%; K, 0.15–0.56%; sodium (Na), 0.06–0.3%; calcium (Ca) and magnesium (Mg), 22.67–47.6 mg/100 g; copper (Cu), 2.0–9.5 mg/kg; iron (Fe), 2.0–9.3 mg/kg; zinc (Zn), 5.7–11.5 mg/kg; and sulfur (S), 128–548 mg/kg.

Vermicompost has a higher concentration of macro- and micronutrients than regular compost (Garg and Kaushik 2005). It contains 9.8–13.4% organic C, 0.51–1.61% N, 0.19–1.02% P, and 0.15–0.73% K. The nutrients in vermicompost are in water-soluble forms, so they are immediately available for plant use (Ndegwa and Thompson 2001; Suthar 2009). In comparison to the original state, Nedunchezhiyan et al. (2011) have reported that vermicompost made from biomass and by-products of tuber crops had greater amounts of N (1.12–2.23%), P (0.26–0.88%), and K (0.33–1.29%). The vermicompost prepared from sweet potato dry leaves had the highest N (2.23% and 2.03%), P (0.88% and0.69%), and K (1.29% and 0.84%) content than other tuber crop wastes.

2.6 *Improves the Physical Properties of Soils*

Due to soil application of compost, improvement of soil structure occurs because of increased porosity and decreased bulk density of amended soil. In addition, organic matters contain polysaccharides and other polymeric substances, which help to improve micropores in the soil. Vermicompost has been shown in limited experiments to enhance macropore space in the range of 50 to 500 μm, resulting in a better air-water connection in the soil, which benefits plant growth (Marinari et al. 2000). The following are some of the advantages of soil physical qualities.

- Adding aggregate-stabilizing humus to composts reduces soil bulk density and improves soil structure by adding organic matter to heavy soils. Incorporating

composts into compacted soils can also help with root penetration and turf establishment.
- Directly enhances the soil's water-holding capacity by binding water to organic matter and indirectly by improving the soil structure, which improves water absorption and movement. As a result, water usage and irrigation will be minimized.
- Reduces the soil-dispersion action of beating raindrops, increases infiltration, reduces water runoff, and increases surface wetness to protect the surface soil from water and wind. In addition, protecting streams and sustaining the health and productivity of the soil requires preventing erosion.
- The fungi or actinomycetes mycelia present in the compost assist in bonding the soil particles into crumbs and strengthening the soil's resilience against wind and water erosion.
- It increases soil aeration, allowing enough oxygen to reach the roots and removing excess carbon dioxide from the root area.
- Increases soil temperature both directly and indirectly through enhanced soil structure by its dark color, which increases heat absorption by the soil.
- It aids moderate soil temperature and the prevention of rapid soil temperature fluctuations, resulting in a better environment for root growth. This is especially true when compost is utilized as a surface mulch.

2.7 Enhances the Chemical Properties of Soils

The benefits of the chemical properties of soil are as follows.

- After composts are applied to soils, they enable soils to hold more plant nutrients and boost cation and anion exchange capacity for extended periods. This is especially significant in soils with minimal clay and organic matter.
- Increases the amount of nutrients in the soil. Composts include vital micronutrients or trace elements like copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), boron (B), and molybdenum (Mb), as well as the primary nutrients necessary by all plants [N, P, K, calcium (Ca), magnesium (Mg), and sulfur (S)]. In addition, the nutrients in mature composts are released to the plants slowly and steadily. Therefore, the benefits will last for several seasons.
- Reduces nitrogen losses by stabilizing volatile nitrogen in raw materials into large protein particles during composting.
- Provides active agents, such as growth substances, which may be beneficial mainly to germinating plants.
- Adds organic matter and humus to regenerate poor soils.
- Buffers the soil against rapid changes due to acidity, alkalinity, salinity, pesticides, and toxic heavy metals.

2.8 Improves the Biological Properties of Soils

The benefits of the biological properties of soils are as follows:

- Provides food for beneficial microbes and earthworms and encourages their growth.
- Aids in the suppression of plant diseases, soil-borne diseases, and parasites.
- Composts have been demonstrated to help prevent plant diseases (such as *Pythium* root rot, *Rhizoctonia* root rot, chili wilt, and parasitic nematode) and reduce crop losses. Specific composts, particularly those made from tree barks, have been found to release compounds that prevent some plant infections, according to research. Five pathways have been proposed for disease control with compost:

  (1) Beneficial microorganisms successfully compete for nutrients.
  (2) Beneficial microorganisms produce antibiotics.
  (3) Beneficial microorganisms successfully predate pathogens.
  (4) Composts activate disease-resistant genes in plants.
  (5) Pathogens are killed by high temperatures caused by composting.

2.9 Mechanism/Process of Composting and Vermicomposting

Waste separated from plastic, glass, and metal pieces should be used. From the nature of waste, its approximate C/N ratio can be judged. This will help in adding dung, cow urine, biofertilizers, etc. The raw waste can be spread in long heaps in the shed. Every layer of about 0.2 m should be sprinkled with a small quantity of superphosphate in the form of rock phosphate, starter compost, decomposing culture, and drenched with water. If needed, *Azospirillum* can be added. The height of the heap will finally be about 0.75 m. This should be sprayed with water at least once a day. Slowly the heap will start heating within approximately 4 to 6 days. The various phases of composting and vermicomposting are briefly discussed.

Mesophilic Stage The soluble components of organic material will start to break down with the small increase in the temperature up to 35 °C. The stage would last for 5–6 days. No turning should be given at this state.

Thermophilic Stage Soon, the heat-generating bacteria increase, and the heap temperature will rise at least for a couple of days to 60 °C or even above. The temperature rise will depend upon moisture, aeration, and types of wastes. Peak temperature may reach within about 10–15 days and then start lowering. The entire stage may take 20 to 25 days. It helps to kill weed seeds and unwanted insects if any. The pH (7.0–7.5) should be checked and corrected accordingly.

Cooling Phase If there is no uniform decomposition, the temperature may rise once or twice. The temperature may be recorded daily. Once the temperature reaches around 30 °C, the material is fit for the release of worms. If material is outside the shed, it should be shifted to the shed and spread in layers. Each layer should be sprinkled with dung/slurry, Karanja, neem cake, slurry mixed with bacterial cultures, and soil described earlier. The heap should be raised to a height of 0.75 m at the center, above ground level. The heap should be observed for at least 2–3 days for a change in temperature. If it does not rise much beyond 30 °C, it is time to release worms.

2.10 Microorganisms Involved in Composting and Vermicomposting

Bacteria, fungi, and actinomycetes, mostly decomposing organisms, are involved in composting and vermicomposting.

Decomposing Organisms

All bacteria and larger organisms involved in the breakdown of organic materials are classified as decomposing organisms. The microorganism populations are impacted by the characteristics of the feeding substrate and the season (Nedunchezhiyan et al. 2011). According to Suthar and Singh (2008), the release of intermediate compounds during composting affects worm growth, reproduction, and microbiota composition. Hot and dry conditions facilitate the proliferation of bacteria and fungi during vermicomposting. However, during the same time span, earthworms (which feed germs) grow and develop at a slower rate (Nedunchezhiyan et al. 2011).

On the other hand, wet and humid conditions favor higher earthworm and actinomycetes populations during vermicomposting. However, diverse organisms may reach a microbiological equilibrium that determines the ultimate population (Nedunchezhiyan et al. 2011). For example, cassava waste/by-products sustain a higher microbial population during vermicomposting than other tuber crop wastes/by-products. This could be because fewer earthworms eat microbes and organic waste (Nedunchezhiyan et al. 2011).

Bacteria are the most common microorganisms that decompose organic matter. They arrive with the organic material and immediately begin breaking it down for their food. Bacteria develop and multiply when the conditions are ideal for them and then die off to make room for others. Bacteria, actinomycetes, and fungi are all first-level decomposers, which devour waste directly. Larger species such as earthworms, beetles, mites, sowbugs, whiteworms, and flies assist them by directly consuming waste. Second-level decomposers like springtails, mold mites, feather-winged beetles, protozoa, and rotifers devour first-level decomposing microorganisms. Finally, third-level decomposers, such as centipedes, rove beetles, ants, and predatory mites, devour first- and second-level decomposers. As a result, species at all levels of the food web contribute to the control of populations at lower levels.

Bacteria

Bacteria "invade" organic tissue when they come into contact with it, consuming and digesting it and breaking it down into simpler forms for other bacteria and creatures to ingest. Bacteria are nutritionally diversified as a group, which means they can devour nearly anything, living or dead. Bacteria require organic materials for both nitrogen and carbon. Bacteria use carbon as an energy source and generate heat and CO_2 by oxidizing carbon. Their primary source of protein is nitrogen, which is required for bodybuilding and population growth.

Actinomycetes

Actinomycetes are second in number to bacteria. They are necessary for humus formation. They release carbon, nitrate-nitrogen (NO_3), and ammonium nitrate (NH_4), allowing plants to access nutrients.

Fungi

Fungi are less numerous than bacteria or actinomycetes, but they have a larger body mass. Fungi feed on decomposing organic matter and acquire energy by breaking it down. For example, fungi play a significant role in breaking down these compounds in lignin- and tannin-rich organic materials.

Earthworms

Invertebrates belonging to the kingdom Animalia, the phylum Annelida, the class Clitelatta, and the subclass Oligochaetae are earthworms. The Megascolecidae and Lumbricidae families of terrestrial Oligochaeta are the two most influential families. More than half of all known species are Megascolecids, which are found throughout Asia, Australia, and the Pacific Oceanic Islands. The Lumbricidae family, on the other hand, is important for human welfare and is native to the United States and Europe but is now distributed all over the world (Edwards and Lofty 1977; Edwards and Bohlen 1996).

3 Fruit, Vegetable, Root, and Tuber Crop Compost

The fruit and vegetable industry produces a lot of biowastes. Recycling strategies are based on the recovery of waste materials after significantly altering their features (Williams and Anderson 2006). Aerobic composting has been an eco-friendly process of converting organic waste into organic fertilizer for thousands of years. However, because of biogas' energy recovery, anaerobic digestion is a more appealing technique for producing fertilizers from fruits and vegetable wastes (FVWs) (Sharma et al. 2000).

Table 8.1 Nutrient compositions of fruit and vegetable wastes (FVWs) used in co-composting

Materials	MC FW	C (%) DW	N (%) DW	C/N **DW**	P (%) DW	K (%) DW	Ca (%) DW	Mg (%) DW
Spinach	89.26	29.82	4.73	6.31	0.22	4.06	1.95	0.24
Cabbage	87.93	35.56	2.88	12.36	0.17	2.73	0.73	0.18
Mustard	91.89	31.30	6.12	5.11	0.27	3.92	3.87	0.39
Carrot	89.93	34.99	1.91	18.35	0.13	2.59	0.23	0.10
Cucumber	96.71	34.55	2.00	16.46	0.07	2.31	0.28	0.12
Orange	81.27	35.25	0.67	53.01	0.03	0.98	0.63	0.13
Pineapple	84.31	36.37	0.78	46.75	0.06	2.35	1.57	0.26
Apple	84.60	35.91	0.39	90.92	0.07	1.80	0.22	0.07
Banana	70.99	34.33	0.56	60.97	0.05	2.10	0.05	0.24
Watermelon	89.72	30.14	2.67	11.31	0.20	3.83	0.45	0.33
Sweet melon	90.58	32.79	1.97	16.62	0.15	3.15	0.36	0.32

MC FW moisture contents fresh weight, *DW* dry weight

By 2025, global solid waste generation is expected to rise from around 3.5 million tonnes per day in 2010 to over 6 million tonnes per day (Hoornweg and Bhada-Tata 2012). FVWs are extremely putrescible plant-tissue waste created on farms, marketplaces, or houses. Fruit and vegetable processing and consumption, for example, accounts for almost 25–30% of waste from peels, seeds, and inedible components. When such wastes are not properly disposed of, they offer significant environmental risks, such as greenhouse gas emissions as they degrade (Vilariño et al. 2017; Saini et al. 2019). FVWs have a low C/N ratio of >27:1 (Esparza et al. 2020). Indigenous microorganisms are microbial inoculants produced at home and can be produced from the kitchen; FVWs are all geared towards increasing the speed of compost maturity or shortening the duration of composting time (Aminah et al. 2016).

Co-composting municipal solid wastes and FVWs for proper disposal and usage has been studied. FVWs could be used as a nitrogen source for plants when composted (Tratsch et al. (2019). Co-composting municipal solid wastes such as garden waste and food market waste produced higher-quality compost with agronomic qualities appropriate for use as organic fertilizers and no phytotoxic effects (Jara-Samaniego et al. 2017). In another study, co-composting with vegetable wastes and paper in a 4:1 (C/N 22.9) ratio produced a higher-quality compost than composting with vegetable wastes and cartons in a 3:1 (C/N 31.8) ratio (Rawoteea et al. 2017). While composting FVWs with yard wastes in a 2.5:1 ratio generated a higher-quality compost than composting vegetable wastes, tree leaves, and grass cuttings individually (Katre 2012).

A survey of the types and volumes of generated FVWs was conducted at the Serdang wet market in Selangor, Malaysia. The survey was conducted over 3 days, with the average proportion of FVWs created only for waste being calculated and examined separately. From the preliminary study, 70% of the waste from the wet market was made up of fruits, while 30% was made up of vegetables. The composition of FVWs and their physical and chemical properties are shown in Table 8.1.

These materials have a moisture level greater than 70%. Before composting, standing water from the FVWs was drained off, and the moisture content of the co-mixed compost materials was kept below 60%. Therefore, the composting process can be significantly aided by keeping the moisture level of the composting materials between 40% and 60%. FVWs are high-nitrogen-containing materials, particularly green plants like spinach and mustard. Except for watermelon and sweet melon, the C/N ratio of vegetables was less than 20, although it was greater for fruit wastes.

3.1 Tropical Tuber Crops Composting: Case Study

Tropical root and tuber crops are considered as third most important food crops after cereals and grain legumes. The commonly domesticated tropical root and tuber crops are cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), yams (*Dioscorea* spp.), taro (*Colocasia esculenta*), elephant foot yam (*Amorphophallus paeoniifolius*), etc. Root and tuber crops are harvested after fully weathering of shoots except for cassava and sweet potato. Further, shoot yield is lower than tuber (economic part) yield. Hence, shoot as waste in tuber crops is less. However, tuber crop-processing industries discharge a lot of wastes. Among root and tuber crops, cassava occupies the first position in area and production at the global level. It is cultivated for its starchy tuberous root, a major carbohydrate source. Therefore, cassava processing is viewed as a cause of pollution and a drain on natural resources, particularly in places where the industry is concentrated. Cassava processing for starch extraction generates a lot of effluents (liquid waste) with a lot of organic content and solid fiber debris (thippi), which is left out when the fresh tubers are crushed. According to an estimate from starch suppliers and industrial traders of Tamil Nadu (India), there are more than 800 starch-producing industries and over 550 sago-producing plants, generating nearly 250 tons of solid waste (thippi) every year (Manickam and Thangavel 2013). Thippi discharged after starch extraction from tubers is poor in all the plant nutrients, besides having a very wide C/N ratio (82:1) (Chithra et al. 2017). To minimize the pollution caused by thippi, it can be converted into nutrient-rich organic manure through composting. Cassava and sweet potato yield a considerable amount of biomass (Suchitra et al. 2010). The leaves and immature stems/vines of these crops are good sources of organic matter and nutrients. The vegetative parts of these crops are either plowed back or burned. The by-products of these root crops can be used to improve soil fertility.

3.1.1 Composting Procedure

Chithra et al. (2019) developed a cassava thippi composting technique. As thippi is very poor in all essential elements and have a wider C/N ratio, first it is to be enriched with N-, P-, and K-rich raw materials, viz., cow dung, cassava leaves, *Gliricidia sepium* (Jacq.) leaves, and *Azolla pinnata* (R. Br.) as N source; Mussooriphos (naturally occurring tricalcium phosphate) as P source; and rock powder as K source for nutrients enriching and reducing C/N ratio (Jimenez and Garcia 1989). In addition to the above composting agents such as microbial cultures, viz., microbial consortium containing *Trichoderma* spp., P and K solubilizers, waste management culture, and earthworm (*Eudrilus eugeniae*) can also be added for quicker decomposition. Regarding the proportion of different components for composting, for every 2.5 kg thippi, 500 g of cow dung and 100 g each of Mussooriphos and rock powder were added. In addition to the above, as N source, either 500 g *Azolla pinnata* or 500 g *Gliricidia sepium* leaves or 250 g each of cassava and *Gliricidia* leaves were added. The composting agents, viz., waste management culture/mixed inoculum/earthworm, were added at 100 g to the above mixture. Composting was done in huge plastic basins measuring 0.8 m in diameter and 0.5 m in height, with fabricated metallic wire mesh lids to provide aeration and insect control. Proper moistening of the mixture was done at periodic intervals to maintain sufficient water for enabling decomposition. After 2 months, compost is ready to use.

3.1.2 Nutrient Content of Thippi Compost

The nutritional study of thippi compost found that thippi enhanced with organic materials such as farmyard manure, *Gliricidia*/cassava leaves, Mussoriphos, and rock powder and composted with earthworm had a high nutrient content in terms of primary, secondary, and micronutrients. The nutrient content of mature compost was high in all the essential plant nutrients with 2.09% N, 1.63% P, 0.49% K, 2.67% Ca, 1.4% Mg, 49.6 mg/kg Cu, 121.3 mg/kg Zn, 344 mg/kg Fe, and 76.3 mg/kg Mn (Chithra et al. 2013). The N, P, K, Ca, Mg, Fe, Mn, Cu, and Zn content in thippi compost was 3.5, 49.7, 32.5, 8, 185, 100, 2.5, and 12 times higher than the raw thippi, respectively (Chithra et al. 2019). The C/N ratio of the compost was 8:1 against 82:1 of raw thippi. Nedunchezhiyan et al. (2011) reported that cassava thippi took 40–43 days to convert completely to vermicompost, whereas all other biomass and by-products took longer (43–65 days). The increase of earthworm weight and the population was higher in vermicompost made from cassava and sweet potato thippi. The vermicompost prepared from biomass and by-products of tuber crops had fairly higher levels of N (1.12–2.23%), P (0.26–0.88%), and K (0.33–1.29%) (Nedunchezhiyan et al. 2011). The vermicompost prepared from sweet potato dry leaves had the highest N (2.23% and 2.03%), P (0.88% and 0.69%), and K (1.29% and 0.84%) content (Nedunchezhiyan et al. 2011).

Vermicompost prepared from root and tuber crops waste applied plants showed $<$10% leaf blight incidence in taro and 0–50% collar rot incidence in elephant foot yam, and yield increase of 14–70% was also noted in both crops (Veena et al. 2013). A 2-year study data on cassava tuber yield showed thippi compost (24.66 t/ha) to be a viable alternative to farmyard manure (26.64 t/ha), green manuring in situ with cowpea (27.18 t/ha), crop residue incorporation (25.03 t/ha), vermicompost (22.15 t/ha), coir pith compost (21.78 t/ha), NPK up to 50% (26.55 t/ha), 2.5 kg $MgSO_4$/ha (27.94 t/ha), and 2.5 kg $ZnSO_4$/ha (24.44 t/ha) (Chithra et al. 2019). Asciutto et al.

(2006) also found the use of organic amendments like agro-industrial wastes after composting in farming as effective means of improving soil structure, enhancing soil fertility, and increasing crop yields. There was no fiber or cyanide content in the thippi compost (the thippi compost had carbohydrate (starch) 15 times less than thippi and cellulose 7 times lesser than thippi). Still, the enhancement in protein was remarkable to 3.5 times that in thippi (Chithra et al. 2017).

Application of thippi compost increased soil pH, soil organic C, and primary, secondary, and micronutrients (Chithra et al. 2019). The population of bacteria, fungi, and actinomycetes in postharvest soil samples was very high in thippi compost applied fields compared to thippi where bacteria alone were seen (Chithra et al. 2017). Economic analysis of the cost of production of thippi compost from thippi indicated a recovery efficiency of 95% with a cost of INR 10.15/kg for its production (Chithra et al. 2019). The economic analysis on the use of thippi compost in all the treatments gave a better benefit-cost (B/C) ratio of more than 1.5 (Chithra et al. 2019).

Good quality nutrient-rich organic manure (thippi compost) could effectively replace other organic manures and effect a saving of up to 50% on chemical fertilizers (NPK). In addition, this green technology can effectively mitigate the environmental hazards posed by starch factory waste. It was also established that applying thippi compost in the soil can improve the soil physicochemical and microbiological properties, enhance soil fertility, and give higher economic benefits. If wisely utilized, this green technology can increase crop productivity and quality and sustain soil health and environmental quality.

4 Conclusion and Perspectives

The five major global issues of the twenty-first century are soil degradation, greenhouse effect, water scarcity, land disposal of solid waste, and agricultural sustainability. Under these circumstances, the recycling of organic wastes has to be given importance in considerably mitigating the above significant issues. Intensive agriculture has resulted in a buildup of negative nutrient balance in soil over the years. As a result, the gap between nutrient demand and nutrient supply is widening. By 2020 A.D., this gap may reach a level of 7.2 million tons per year. To avert food scarcity and sustain continuing agricultural expansion, soil fertility and productivity must be restored and maintained at a high level. In the long run, it appears that recycling organic substrates into the soil to improve soil fertility and crop yield is a more practical method.

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Part IV
Enzymes, Biofuels and Other Novel Applications

Chapter 9
Vegetable and Fruit Wastes: Utilization in Novel Industrial Applications

Gargi Ghoshal

Abstract Annually vast quantities of waste are produced from vegetables and fruits industries – a vital food industry sector. The waste is mainly composed of peels, pomaces, rinds, and seeds. They comprise an excellent source of bioactive nutraceuticals, dietary fibers, vitamins, enzymes, peel/seed oils, pigments, polyphenols, etc. The bioactive compounds are antioxidant, anticancer, anti-inflammation, anti-allergenic, and anti-atherogenic in nature, having an encouraging effect on human healthiness. Therefore, these phytochemicals have potential applications in different industries, especially in food and pharmaceuticals, to manufacture functional foods and nutraceuticals. The current chapter discusses various types of fruit and vegetable wastes, their composition, recovery, health beneficial effect, and utilization.

Keywords Vegetables and fruits waste · Plant bioactive · Nutraceuticals · Extraction · Antioxidants · Bio-pigments

1 Introduction

Food processing industries in the European Union generate 100 MT of food waste per annum, accounting for 35% loss during the harvesting and processing. The approximate amount of industrial production of food wastes is 26% from beverage industry, 21.3% from dairy and dairy products including ice cream, 14.8% from fruit and vegetable industry, etc. (Baiano 2014; Arshadi et al. 2016). Substantial quantity of biomolecules having opportunity for human consumption is lost at the time of food processing, such as drying, pasteurization, extraction, milling, mixing, cooking, and extrusion (Galanakis 2013; Shivhare et al. 2013). The efficient use of food industry waste and food industry by-products has an enormous prospective for achieving functional nutraceutical composition. For example, valorization of these

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wastes might be accomplished by isolating the expensive components such as essential oils (EO), polyphenols, pigments, flavor compounds, proteins, enzymes, polysaccharides, and dietary fibers using diverse separation techniques (Barba et al. 2016; Roselló-Soto et al. 2016; Zhu et al. 2017).

Fresh fruits and vegetables have importance in our diet and human life. Thus, validation for such essential food products has enhanced considerably due to the progressing world population and altering dietary composition (Vilariño et al. 2017). According to the Food and Agriculture Organization (FAO), a minimum of 33.33% of all food produced worldwide (about 1.3 billion metric tons) is wasted and lost each year (FAO 2014). However, waste from one food sector can be repurposed as raw materials for another food industry that is fit for consumption (Parfitt et al. 2010; Panda et al. 2018). Buzby et al. (2011) approximated that on the whole worth of fruit and vegetable leftovers for trader or end-user stage was $42.8 billion and $141 per head, respectively, in 2008 in the USA.

2 Composition of Vegetable and Fruit Waste

Rapid growth has been seen in food processing industries worldwide for the past few decades. These have resulted in generating a substantial amount of wastes. Total food and beverage waste is calculated and found approximately to be 14 MMT in the UK; 20% of the waste is related to processed food, supply, and retail (Parfitt et al. 2010). These huge quantities of wasted food cause enormous environmental inconvenience due to their perishable nature; they release hazardous greenhouse gasses and decay landfills (Vilariño et al. 2017; Gowe 2015). In Table 9.1, by-products of different fruits and vegetables wastes (FVWs) are discussed. FVWs are the precious foundation of potentially valuable bioactive compounds. They are unique nourishing elements of minerals, pigments, sugars, fibers, phenolics, organic acids, proteins, lipids, and other compounds listed in Tables 9.2 and 9.3. Recovered elements fetch more price than authentic food (Fig. 9.1).

Generally, kernel or pulp is utilized in fruits and vegetables products manufacturing. Still, huge quantities of indispensable phytochemicals such as polyphenols, antioxidants, minerals, and vitamins exist in the non-consumable fraction such as peels, seeds, and rest of the parts of fruits and vegetables (Sagar et al. 2018). Lemon peels, grape peel and seed, orange peel and seed, avocado seeds, jackfruit seeds, and mango seeds retain 15% higher phenolic compound as compared to fruit pulp (Table 9.3).

Table 9.1 By-products from different fruits, vegetable, and plantain crop wastes and their uses[a]

Sl. no.	Fruits/ vegetables	Waste	Utilization
1	Apple	Pomace	Fresh pomace can be used to make apple chutney and pectin and vinegar production
2.	Apricot	Apricot kernel	Used in making apricot oil, and de-oiled apricot cake can be used for cattle feed
3	Grape	Stem, seed, and pomace	Stem is used for cream of tartar; seeds can be used for seed oil manufacturing. Pomace can be used to make chutney. Cold store juice produces potassium hydrogen tartrate
4.	Guava cheese	Core, seed, and peels	Guava cheese, pectin production
5.	Jackfruit	Thick rind and seeds	Used in pectin manufacturing and in making high-class jelly. Starch and flour are recovered from seeds, suitable for diabetic patients
6.	Mango	Stones and peels	Peel can be used to make vinegar; stone is used to recover starch. Peel can be used to make pectin
7.	Passion fruit	Thick hard rind	Pectin is recovered
8.	Peach	Peach kernel	Can be used to make kernel oil
9.	Pear	Peel and core	Can be fermented into alcoholic beverage called *perry* which can be further fermented to fruit vinegar
10	Pineapple	Shell and trimmings, top and bottom	Shell and trimming extract after fermentation produces alcohol for automobile use. From juice, vinegar is made. The rest of the peel and other parts are used for animal feed manufacturing. Top and bottom can be ensiled with molasses and urea and can be used to make cattle feed. Bromelain enzyme extracted is used as meat tenderizer and beer clarifier
11	Banana	Peel and stem	Can be used to make banana cheese similar as guava cheese. Starch can be recovered from stem. Banana fiber can be recovered from peel
12	Papaya	Latex and peel	Latex can be used to make proteolytic enzyme papain. Peel is a very good source of pectin
13	Citrus fruits (orange, lemon)	Peels, seeds, and sludge	Used to make seed and peel essential oils and citrus pectin; citric acid can be made from sludge
14	Cashew	Cashew apple	Processed into juice and a distilled alcoholic beverage, *fenni*, in India. Wine is made from cashew apple juice
15	Peas	Vine and pea hulls	Can be used to make stock feed
16	Tomato	Skin and seed	Used to make pectin and seed oil
17	Other vegetables	Peel and other parts	Can be used for animal feed
18	Sweet potato	Skin and bagasse	Can be used for animal feed, *shochu* (alcoholic drink), and silage

(continued)

Table 9.1 (continued)

Sl. no.	Fruits/ vegetables	Waste	Utilization
19	Cassava	Skin, rind, and bagasse	Biochar, single-cell protein, biocomposites, biofuels, and silage
20	Oil palm	Bagasse	Organic fertilizers, animal feedstock, and soil conditioner
21	Date palm fruits	Skin, seed, and bagasse	Biofuels, biopolymers, biosurfactants, and organic acids
22	Coconut	Coconut fiber	Used in rope making, floor mats, doormats, brushes, mattresses, coarse filling material, and upholstery; soil conditioner

[a]Sources: Ray et al. (2011), Gowe (2015), Chandrasekaran and Bahkali (2013), and Panda et al. (2018)

Table 9.2 Composition of different fruit and vegetable wastes

Sl no.	Fruit waste	Chemical composition (in g/100g)					
		Moisture	Proteins	Fat	Minerals	Fibers	Carbohydrates
1	Apple pomace	_	2.99	1.71	1.65	16.16	17.35
2	Mango seed kernel	8.2	8.50	8.85	3.66	_	74.49
3	Jackfruit (inner and outer portion	8.5	7.50	11.82	6.50	30.77	14.16
4	Jackfruit seeds	64.5	6.60	0.40	1.20	1.50	25.80
5	Jack seed flour	77.0	2.64	0.28	0.71	1.02	18.12
6	Passion fruit peel	81.9	2.56	0.12	1.47	5.01	_
7	Banana peel	79.2	0.83	0.78	2.11	1.72	5.00
8	Sweet orange seeds	4.00	15.80	36.90	4.00	14.00	_
9	Watermelon seeds	4.3	34.10	52.60	3.70	0.80	4.50
10	Muskmelon seeds	6.8	21.00	33.00	4.00	30.00	_
11	Pumpkin seeds	6.0	29.50	35.0	4.55	12.00	12.53
13	Central core	93.1	0.30	0.03	1.04	0.68	1.20
14	Outer hard fibrous sheath	91.9	0.12	0.06	0.98	1.81	2.44
15	Press juice from stem	98.6	0.05	_	0.63	_	0.41

Sources: Mani and Sethi (2000) and Gowe (2015), updated

3 Identification of Functional Biomolecules in FVWs

Various bioactive components possess health beneficial characteristics such as cardioprotective, antimicrobial, antiviral, antitumor, and antimutagenic performances (Yahia 2017). Various fruits (i.e., oranges, apples, peaches, pineapples) and vegetables (i.e., carrots, artichoke, green peas, potatoes, onions, and asparagus) are used for juice and pulp extraction, frozen pulp manufacturing, and puree, jam, and jelly production and form a significant amount of industrial waste (Tables 9.1 and 9.3).

Table 9.3 Fiber, phenolic content, and flavor recovery from fruit and vegetable wastes

Fruit/ vegetable waste	Nature of waste	Typical losses and waste (%)	TDF (%)	IDF (%)	SDF (%)	Phenolic compound	Microbial flavor	Microbial color
Apple	Pomace, peel, and seeds	–	Peel, 0.91 Pomace, 88.5	0.46 66.9	0.43 18.6	Hydroxycinnamates, phloretin glycosides, quercetin glycosides, catechins, procyanidins	Pineapple (ethyl butyrate) using strain *Ceratocystis fimbriata*	–
Apricot	Seed	–	27–35	–	–	–	–	–
Banana	Peel	35	50	IDF/SDF = 5.46:1		Carotenoids (palmitate or caprate, xanthophylls, laurate)	–	–
Citrus	Rag, peel, and seeds	50	14	9.04	4.93	Eriocitrin, hesperidin, naringin	–	–
Cranberry	Seeds	–	51.06	45.93	5.13	(+) Catechin, procyanidin B1, (−) epicatechin, myricetin-3-xylopyranoside, quercetin-3-O-galactoside, dimethoxymyricetin-hexoside, methoxyquercetin pentoside	–	–
Dates	Seeds	–	57.87 to 92.4	–	–	–	–	–
Dragon fruits	Rind, seeds	30–45	–	–	–	–	–	–

(continued)

Table 9.3 (continued)

Fruit/ vegetable waste	Nature of waste	Typical losses and waste (%)	TDF (%)	IDF (%)	SDF (%)	Phenolic compound	Microbial flavor	Microbial color
Durian	Skin, seeds	60–70	–	–	–	–	–	–
Grapes	Skin, stem, and seeds	20	Pomace, 77.9–77.2 Seeds, 40	68.4–73.5	3.77–9.5	Procyanidins, catechins, anthocyanins, stilbenes, flavonol glycosides, Epicatechin, epigallocatechin, picatechin gallate	–	Carotenoids using *Monascus purpureus* and *Penicillium chrysogenum* in SmF
Guava	Peel, core, and seeds	10	–	–	–	–	–	–
Jackfruits	Rind, seeds	50–70	–	–	–	–	–	–
Kiwi fruits	Pomace	–	25.80	18.70	7.10	Caffeic acid, protocatechuic acid, p-coumaric acid	–	–
Mango	Peel, stone	45	51.22	–	–	Gallates, gallotannins, gallic acid, ellagic acid, flavonol glycosides	–	–
Mangosteen	Skin, seeds	60–75	–	–	–	–	–	–
Onion	Outer leaves/ skin	–	68.3	–	–	Quercetin-3,40-O-diglucoside and quercetin 40-O-monoglucoside	–	–

Orange	Peel	–	57	47.6	9.42	Hesperidin	–	Carotenoids using strain *Monascus purpureus* and *Penicillium purpurogenum* in SSF and SmF
Papaya	Rind, seeds	10–20	–	–	–	–	–	–
Passion fruits	Skin, seeds	45–50	–	–	–	–	–	–
Pineapples	Core, skin	33	–	–	–	–	–	Carotenoids using strain *Chryseobacterium artocarpi* in SmF
Peach	Pomace	–	54.5	35.5	19.1	–	–	–
Pear	Pomace	–	43.9	36.3	7.6	–	–	–
Pumpkin	Pomace	–	76.94			–	–	–
Raspberry	Pomace	–	77.5	75	2.5	–	–	–
Carrot	Pomace	–	63.6	50.1	13.5	Carotene (α and β)	Banana (isoamyl acetate) using strain *Ceratocystis fimbriata* Vanillin using *Pycnoporus cinnabarinus*	–
Sugar beet pulp	–	–	–	–	–	–	Vanillin using strain *Aspergillus niger*	–
Olive press cakes	–	–	–	–	–	–	δ-Decalactone (coconut) and γ-decalactone using strain of *Ceratocystis moniliformis* and *Pityrosporum ovale*	Astaxanthin using *Xanthophyllomyces dendrorhous* in SSF

(continued)

Table 9.3 (continued)

Fruit/ vegetable waste	Nature of waste	Typical losses and waste (%)	TDF (%)	IDF (%)	SDF (%)	Phenolic compound	Microbial flavor	Microbial color
Garlic	Husk	–	62.23	58.07	4.16	Di-ferulic acid, hydroxybenzoic acid, p-coumaric acid, caffeic acid-O-glucoside, coumaric acid-O-glucoside, caffeoylputrescine	–	–
Green chilly	Peel and seeds	–	80.41	–	–	–	–	–
Peas	Shell/ hull	40	91.5	87.64	4.1	–	–	–
Potato	Peel	15	5.6	–	–	Chlorogenic, gallic, protocatechuic, and caffeic acids, chlorogenic acid isomer II	–	–
Rambutan	Skin, seeds	50–65	–	–	–	–	–	–
Tomato	Core, skin, and seeds	20	50	25	25	Lycopene		Lycopene
Sugarcane	Juice	–	–	–	–	–	–	Carotenoids using *Rhodotorula rubra* in SmF
Sugarcane	Bagasse	–	–	–	–	–	–	Red pigment using *Monascus ruber* in SmF

Casava waste	Peel and pomace	–	–	–	–	–	–	Carotenoids using *Rhodotorula glutinis* in SmF
Onion peels, potato skin, mung bean husk, and pea pods	Peels and husk	–	–	–	–	–	–	Torularhodin, β-carotene, and torulene using *Rhodotorula mucilaginosa* in SmF and bioreactors
Papaya, Orange, and carrot peels	Peels	–	–	–	–	–	–	β-Carotene *using Blakeslea trispora* in SSF

Source: Sagar et al. (2018), Kaur et al. (2019), and Sharma and Ghoshal (2020), updated
SSF solid-state fermentation, *SmF* submerged fermentation, *TDF* total dietary fiber; *IDF* insoluble dietary fiber, *SDF* soluble dietary fiber

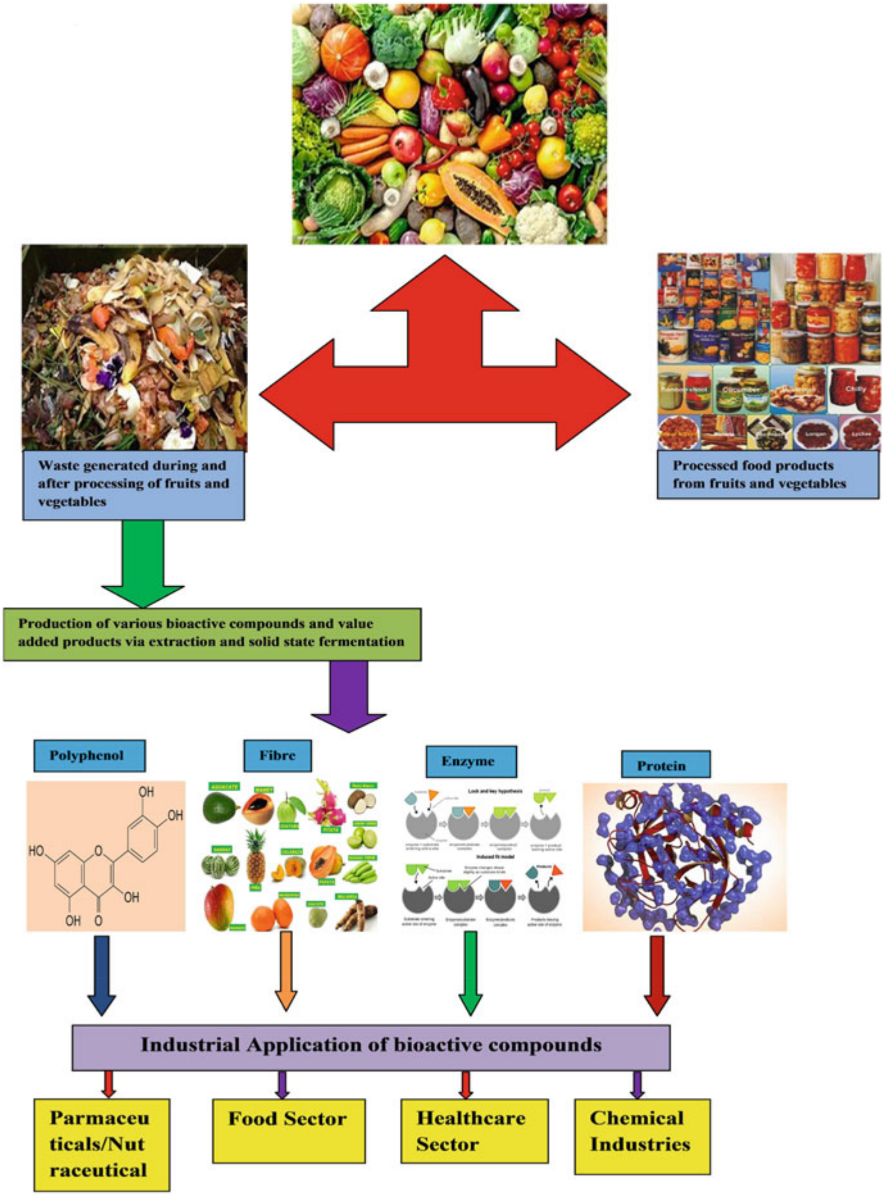

Fig. 9.1 Fruit and vegetable waste compositions and their applications

3.1 Pectin

Pectin is a costly value-added by-product from the fruit and vegetable industry. Particularly fruit peel such as apple, citrus fruits, and seeds are an essential source of pectin. Pectin has extremely crucial uses in food industries as stabilizers and thickeners (Güzel and Akpınar 2018).

Extraction Methods

Numerous methods are prevalent to extract pectin from plant resources. Choosing an appropriate technique for isolation of pectin is necessary to improve its isolation yield and get a superior produce. Among all the separation processes, in conventional practice, e.g., isolation with mineral acids, other processes, e.g., ultrasound extraction, microwave extraction, and enzyme-assisted extraction, follow diverse mechanisms.

Conventional Methods Conventionally, pectin is isolated in acidified water using 0.05–2 M sulfuric, nitric, phosphoric, acetic, or hydrochloric acid between 80 °C and 100 °C temperature for 1 h with continuous stirring (Georgiev et al. 2012). Traditional extraction (solvent extraction) is reliant on various factors such as temperature, pH value, characteristics of the solvent, solid-to-water ratio, time of extraction, dry solids, particle size, and diffusion rate. The highest yield of pectin can be attained at 2.0 pH with hydrochloric acid (Kulkarni and Vijayanand 2010). Nonetheless, some significant disadvantages in this process include excess solvent usage, loss of several volatile components, deterioration of essential targeted components in plant materials, and alteration of pectin structure during isolation because of reaction with extracting solvent and/or co-solutes. Several very important innovative and attractive alternative advancements are as follows.

Ultrasound-Assisted Extraction Ultrasound extraction methods have a hugely beneficial effect over traditional heating methods for extraction. These include less energy expenses, brief handling period, lower solvent utilization, enhanced protection of worker, superior yield, and ecological expression as non-thermal technique (Chemat et al. 2017). During pomegranate (*Punica granatum*) dispensation, a higher amount of by-products is formed. These by-products mostly contain peels (78%) and seeds (22%). They are significant antioxidant resources. By-products from pomegranate have also been a center of research for pectin removal (Moorthy et al. 2015). To separate pectin, ultrasound-assisted extraction (UAE) of 20 kHz was used with an absorbed sonotrode and maximum influence of 130 W. The conventional removal technique was followed at an equivalent temperature of 75 °C for 60 min and at pH 2.0. The investigator achieved an enhanced MW (microwave) yield as 20% or above of isolated pectin when UAE was used. The most guaranteed results were established when the authors used ultrasound-assisted heating extraction (UAHE) (25.9 min), achieving yield of pectin up to 26.74%, whereas in conventional heating extraction (CHE), lesser yield 23.44% after 72.26 min from grape pomace was obtained. The variation in yield of pectin was 12.35% higher in UAHE in contrast to CHE.

UAE extraction method of pectin is established helpful and allows utilizing an environment-friendly function at lesser temperature (in contrast to CHE), at least energy spending. The composition and molecular structure of the pectin were characterized, having galacturonic acid (GalA) 59.12% and arabinose 21.66%

(Chen et al. 2015). Additionally, pectin accumulation significantly enhanced the gelatinization temperature and also gelatinization enthalpy.

Microwave-Assisted Extraction (MAE) Microwave (MW) processing contributes an important function in food science and technology. Nowadays, it is frequently established in research labs and industries as an emerging technique for the (i) dehydration of food products, (ii) isolation of valuable plant materials, and (iii) enzyme and microorganism inhibition and inactivation. MW operates in the range of frequencies 0.3 to 300 GHz, and the radiations are non-ionizing in nature (Barba et al. 2016; Roselló-Soto et al. 2016). While being introduced in the food matrix, MW produces heat after coming in touch with the cellular polar composite. The produced heat acts in response with the molecules resulting in ionic transmission and dipole rotation. MAE is a very rapid process, yield improved substantially, energy consumption was lesser, and less quantity of solvents is resuired. The pectin present in pomelo fruit peels as well as in cell walls is available largely and has some health-related features (diminishing the intensity of cholesterol). The instigator examined that power of MW was an essential feature for pectin extraction from lime bagasse, and thus, the power level of MAE was used in the range 100–500 W. It is confirmed that the pectin yield improved with enhancement of MW power (Chen et al. 2016).

Enzyme-Assisted Extraction (EAE) EAE represents significant profit to isolate pectin from plant origin materials, by-products, and wastes. This method is able to increase yield of pectin as compared to conventional techniques and could be utilized to lower the processing temperature, dropping energy expenditure. EAE can also be accomplished by means of traditional hot water extraction, concerning a lesser quantity of solvent and diminishing the extraction period compared to the green extraction technique.

Usually, cellulase, protease, hemicellulase, lactase, xylanase, polygalacturonase, α-amylase, neutralase, β-glucosidase, endo-poly-galacturonase, and pectinesterase enzymes are used in the pectin extraction process (Yuliarti et al. 2015; Wikiera et al. 2015).

Ghoshal and Negi (2020) studied the isolation of pectin from kinnow (*Citrus nobilis* + *Citrus deliciosa*) peels and its characterization. The study estimated the physicochemical properties and flow behavior of the traditionally extracted pectin using hot water boiling method from the kinnow peel. Pectin separation using hot water from kinnow peel maintaining pH 5 at 90 °C for half an hour of simultaneous precipitation using ethanol and freeze drying yielded 6.13% of pectin. The physicochemical properties of extracted pectin were compared with commercial pectins such as high methoxyl and pure pectin. Additionally flow viscometry in steady-state shear properties and in oscillatory mode dynamic rheological properties were determined. It was confirmed that kinnow peel pectin was low methoxyl pectin. Thus it was confirmed that kinnow peel pectin could be utilized effectively in manufacturing low-calorie jellies and jams and can be used in food products as thickening and gelling agent.

3.2 Nutraceuticals

Polyphenols are the secondary metabolites exist in plant tissues in plenty, Significant amounts of antioxidants are present in fruit wastes also (Ayala-Zavala et al. 2011). Antioxidants from botanical sources and polyphenolics are utilized widely in food, drug, and cosmetic product formula. The key collection of phenolic antioxidants comprises tannins, flavonoids, and phenolic acids. Figure 9.2 depicts the classification of the phytochemical family. Polyphenols have a variety of health benefits, including antibacterial, antioxidant, anti-allergenic, antithrombotic, and anti-inflammatory properties. Quercetin, catechin, and kaempferol are generally studied polyphenolic composites established to lower the hazard of cancer, diabetes, and other chronic diseases such as obesity and cardiovascular diseases (Ghoshal 2020; Ghoshal et al. 2018; Rasouli et al. 2017). The main polyphenolic compounds found in pineapple peel wastes are gallic acid, epicatechin, catechin, and ferulic acid (Li et al. 2014). Polyphenols extracted from pineapple peels using different solvents but yield was the maximum when methanol was used as extracting solvent (21.5% %) as compared to ethyl acetate (4.9%), and water (4.3%). Likewise, phenolic compound extraction was maximum in methanol followed by ethyl acetate extract and water extract (yields were 13.8 ± 0.3 mg/g, 51.1 ± 0.2 mg/g, and 2.6 ± 0.1 mg/g, respectively). The oxygen scavenging activity of one mole of polyphenolic

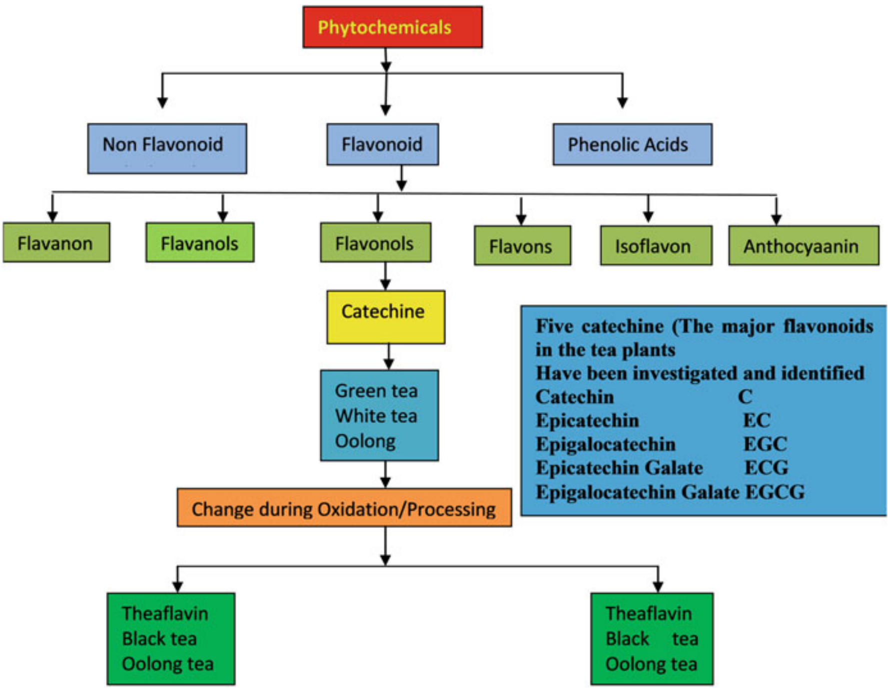

Fig. 9.2 Phytochemical family

compounds existing in pineapple waste like peels was in the order ferulic acid < epicatechin = catechin < gallic acid (Li et al. 2014).

Ferulic acid has possible utilization in food, pharmacy, and cosmetic industries as an aroma and flavor enhancer because the technique demands bio-translation of ferulic acid into vanillin and vanillic acid (Ou and Kwork 2004; Ong et al. 2014). According to Aarabi et al. (2016), it is predicted that as the growth rate is about 6% per annum from 2017 to 2025, trade of vanillin will reach US$ 724.5 million by 2025 globally.

The pomelo fruit is also rich in pectin, vitamin A and E, lignin, fiber, essential oils, total phenolic content (TPC), and terpenoids (Chen et al. 2016).

3.3 Antioxidants

Fruit peels (skins) are affluent in nutrients such as phytochemicals which are effectively applied in medicines or as supplement in food (Chacko and Estherlydia 2014). Antioxidants are an excellent compound to increase the nutritional significance of fruit purees (Bobinaitė et al. 2016; Ayala-Zavala et al. 2010, 2011). The possible anti-oxidative grade and bioavailability of the nutrient present in by-products during the manufacturing of pomegranate nectar were analyzed (Surek and Nilufer-Erdil 2016). Waste like seeds and other residues were recovered from pomegranate nectar sediments. Pomegranate nector sediments consist of peels, filter cake, polyphenols and anthocyanins, also pomegranate nector sediments have better antioxidant activity than those gained from pomegranate nectar.

The tomato waste contains a significant amount of antioxidant activity and total polyphenolics. In tomato skin, it was observed that more than 38.2 and 66.5% of antioxidants and polyphenols were present, respectively, as compared to tomato seeds (Ray et al. 2011; Sarkar and Kaul 2014). Nowadays, grape seed extract has developed attention from dieticians, consumers, and researchers due to the presence of its health beneficial nutraceuticals. Nowshehri et al. (2015) reported that the tomato seeds are the exceptional polyphenol source, particularly phenolic acids, flavones, flavan-3-ols, pro-antioxidants, ellagitannin, catechist, anthocyanins, stilbenes, and resveratrol, having antioxidant, anti-aging, antimicrobial, antitumor, antitoxic, and anti-inflammatory functions for the liver. The extracts of tomato seed have possible application in dietary supplements and medical treatments (Nowshehri et al. 2015). The anthocyanins from grape skins might be utilized for the development of food color. Natural preservatives such as vanillin and geraniol have many applications. The strawberry juices with fiber supplementation stored for 15 days at 5 °C had remarkable consequences in dropping original microbial counts (4–6 log cycles reductions) as compared to control sample, where fiber was not added (Cassani et al. 2016). Albuquerque et al. (2016) analyzed the antioxidant activity of different parts of fruit *A. cherimola Mill* from Madeira Island. Pulp, peel, and seeds of Mateus II, Funchal, Madeira, and Perry Vidal cultivars were analyzed. They established that the Madeira orange peel demonstrated total flavonoids 44.7 in terms of epicatechin equivalents/100 g and highest antioxidant capacity 0.97 mg/mL in terms of EC50. Lutein, the main carotenoid, was present in the range 129–232 μg/100 g, while 4.41 mg/100 g was the highest L-ascorbic acid content found in Perry Vidal cultivar peel waste.

Oszmiański et al. (2016) compared the polyphenolic compounds and antioxidant activity of cranberry fruit (*Vaccinium macrocarpon* L.) and fruit products (juice and pomace). They analyzed leaves also from three cranberry varieties, and they found that leaves and pomace have higher antioxidant activity and TPC as compared to fruits and juices.

3.4 Peel and Seed Oils

There is a considerable possibility of recovering EO and other nutraceuticals, polyphenols, and flavonoids from the peel, seed, and kernel oil from the FVWs. The yield range of fruit seed oils varies from 11.8% to 28.5% (Górnaś et al. 2016). Isolated seed oils contain distinct components and specific phytosterols, fatty acids, and squalene contents. The seed oil recovered from pomegranate is an excellent resource of punicic acids (86.2%). In addition, the seed oil contains oleic and linolenic acids, minerals, iodine, and antioxidants. It has remarkable cytotoxicity recognized by several cell lines such as A549, CHOK1, and SiHa, markers for human lung carcinoma, Chinese hamster, and human cervical cancer cells, respectively. Thus, it is confirmed that pomegranate seed oil is anticancerous (Bayala et al. 2014).

Petkova and Antova (2015) reported that the oils extracted from three melon seed varieties have considerable use in the pharmaceutical industry due to numerous antioxidants and polyphenols.

Lemon EO restrain D-limonene, which gets better resistance, counteract depression and mood swings, endorse clearness in thinking and function, strengthen and promote the brain and body, unwrap and release emotional outburst, repair skin health, and diminish wrinkle formation (Falsetto 2008). In addition, dry bitter orange oil has a curing effect in the prolapsed treatment of the uterus and rectum, piles, and diarrhea (Falsetto 2008).

Citrus peel EO are prospective resources isolated from peel waste yielding about 0.5 to 3.0 kg essential oil from a ton of fruit peels. Citrus EO are important flavoring agents exploited in soft drinks; beverages; confectioneries; cosmetics like soaps, perfumes, and masking agents; and other household products due to the presence of its aromatic flavor. It is used as antibacterial agent in skim and low-fat milk to enhance shelf life (Dabbah et al. 1970; Javed et al. 2011).

3.5 Pigments/Color

FVWs are major potential sources of natural color or pigments (Table 9.3). This color can be extracted from fruit peels, pomaces, or pulp, either by solvent extraction or supercritical extraction process or by fermentation of FVWs (Panda et al. 2018).

Kaur et al. (2019) studied biocolor β-carotene production from FVWs in solid-state fermentation, its categorization was done, and anti-oxidative properties were determined. They optimized biochemical parameters such as temperature, pH, agitation, and substrate concentration for manufacturing of β-carotene in solid-state fermentation from carrot, orange, and papaya peels taking microbial strain *Blakeslea trispora* (+) MTCC 884. Manufacturing of β-carotene was found considerably prejudiced by altering all factors which produce the highest yield of 0.127 mg/mL. The presence of β-carotene was confirmed from liquid chromatography-mass spectrometry (LCMS) results. Furthermore, β-carotene percentage was measured by High Performance Liquid Chromatography (HPLC) and LCMS, and it was found at 76%, with high purity with excellent antioxidant activity as determined by DPPH (2,2-diphenylpicrylhydrazyl) and ABTS (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)).

Sharma and Ghoshal (2020) optimized carotenoid synthesis by *Rhodotorula mucilaginosa* (MTCC-1403) using fruit and vegetable industry wastes in a bioreactor. The agro-industrial waste comprised potato skin, onion peels, pea pods, and mung bean husk. After selecting suitable carbon and nitrogen sources of fruit and vegetable industry waste, different factors of fermentation such as pH 6.1, 25.8 °C temperature, and 119.6 rpm agitation were optimized. Additionally, to assess the outcome of aeration on carotenoid synthesis, 3 L bioreactor was used to perform fermentation under optimum conditions with air incorporation of 1.0 vvm (volume of culture medium)**.** Aeration causes an increase of yield of 100 μg carotenoids on the basis of g of dry biomass. Furthermore, LCMS of isolated pigment established the existence of several other carotenoids, torularhodin, β-carotene, and torulene.

Beetroot peel is a possible resource of precious pigments that are water-soluble and nitrogen-containing, such as betalains, encompassing two major classes, red betacyanins and yellow betaxanthins. Betalains are widely used as natural color with excellent free radical scavengers in the food industry (Azeredo 2009).

3.6 Flavors

Vanillin, with the chemical name 4-hydroxy-3-methoxy benzaldehyde, is manufactured from vanillic acid. Vanillin is the major flavor constituent of vanilla, usually imperative and exceedingly used as food flavor and in pharmaceutical, cosmetics, and detergent sectors (Tilay et al. 2008). After fermentation, the original vanillin flavor is extracted from the pods of vanilla orchids (*Vanilla planifolia*) (Priefert et al. 2001; Baqueiro-Pe˜na and Guerrero-Beltrán 2017).

At the industrial scale, rhamnose is acquired during rutin hydrolysis of citrus fruits. Haleva-Toledo et al. (1999) explained that L-rhamnose is the major constituent of cell wall pectin and it is used as the raw ingredient for the manufacturing of the strawberry flavor "furaneol," 2,5-dimethyl-4-hydroxy-3(2H)-furanone. "Ethyl butyrate," the pineapple flavor, is generated using the microorganism, *Ceratocystis fimbriata*, isolated from apple waste specially from apple pomace (Table 9.3).

Lanza et al. (1976) stated that "δ-decalactone," the coconut flavor, is isolated during a bio-transformation method using *Ceratocystis moniliformis* from olive waste like press cake. Volatile compounds extracted from pineapple processing wastes generated after juice extraction are rind and fibers, and more than 35 volatile constituents were recognized. The main constituents recognized were 29% alcohols, 9% aldehydes, 9% ketones, 6% acids, and 37% esters (Barreto et al. 2013). These characteristics indicate that they are prospective for manufacturing of aromatic natural essential oils, which could further be utilized in products such as juice concentrate made from pineapple to get better sensory attributes (Dorta and Sogi 2017).

Felipe et al. (2017) illustrated three effective manufacturing processes for aroma composite, such as natural extraction, chemical synthesis, and biotechnological extraction methods. Natural flavor synthesis has a rising interest in generating an extensive range of flavors (Table 9.3).

3.7 Fibers

Dietary fiber has enormous health beneficial effect on human diet. It helps to diminish the hazard from developing hypertension, coronary heart disease, stroke, obesity, diabetes, as well as specific gastrointestinal diseases and reduces serum cholesterol and blood pressure. Ghoshal and Mehta (2020) isolated dietary fiber from kinnow peel yielding 47 ± 0.23% *using* enzymatic gravimetric technique. Diverse physiochemical characteristics of kinnow peel and the inaccessible dietary fiber samples were considered. They found that water holding capacity (WHC) and oil holding capacity (OHC) of Kinnow peel fiber were 6.92 g and 1.26 g, correspondingly.

Ghoshal and Dhiman (2020) studied dietary fiber isolation from date fruit. The date is a vital fruit rich in vitamins, minerals, dietary fiber, protein, and sugar that provide rapid energy. It recommends significant health beneficial results such as protection against cardiovascular diseases, constipation, and colon cancer, lowering of cholesterol, regulation of glucose absorption and insulin release, etc. The date fruit dietary fiber extraction was done using the microwave. Categorization of fiber was made using physicochemical, rheological, and elemental analysis, FTIR, and SEM. Particle size was evaluated, and the range was found between 800 and 1067 nm. The extracted water-insoluble dietary fiber has outstanding OHC and WHC, and it is a rich mineral foundation. The FTIR study confirmed the presence of polysaccharides, cellulose, hemicelluloses, and amide, which indicated protein in fiber samples. Atomic absorption spectroscopic study established higher calcium, magnesium, manganese, iron, zinc, phosphorous, and sodium.

Saikia and Mahanta (2016) recovered fibers from six fruits as by-products, e.g., from pomaces, peels, and blossoms of fruits, and compared functional properties and nutritional beneficial effects of extracted fibers. Six fruits such as carambola, pineapple and watermelon peels, Khasi mandarin orange, Burmese grape, and blossom of seeded banana were used for fiber study. Burmese grape peel and seeded banana blossom produced the highest fiber yield with 79.94 ± 0.41 g/100 g and 77.18 ± 0.20 g/100 g, respectively. They also exhibited excellent WHC and OHC, swelling index, and antioxidant activity.

Kammerer et al. reported that higher quantity of dietary fibers such as cellulose, hemicelluloses, and a little amount of pectin was present in grape by-products such as pomace. Gonzalez-Centeno et al. reported stem and pomace by-products from 10 varieties of grapes. They extracted pomace from red grapes "Tempranillo" cultivar which produced the maximum dietary fiber 36.90 g/100 g fresh weight yield, as compared to other parts such as from stem 34.80 g/100 g FW and from fruit 5.10 g/100 g FW. Dietary fiber of mango peels was calculated by Ajila and Prasada Rao (2013), who established that the total dietary fiber yield was in the range 40.6%–72.5%, along with arabinose, glucose, and galactose being the main naturally available sugars among all types of insoluble and soluble dietary fibers. Mango kernel has 2% crude fiber, but mango peel consists of 28.05% total dietary fibers on dry matter basis, whereas soluble fiber of 14.25% and insoluble fiber of 13.8% on dry matter basis (Table 9.3) were reported by Vergara-Valencia et al. (2007).

3.8 Enzymes

FVWs have an inconsistent composition that helps in the growth of diverse microorganisms in producing valuable enzymes by fermentation (Ghoshal et al. 2012; Panda et al. 2016) (Table 9.4).

Several fruit residues (Table 9.4) were utilized as substrates to manufacture amylases. Wastes from banana (Unakal et al. 2012), citrus (Mohamed et al. 2010), date (Said et al. 2014), potato peels (Mushtaq et al. 2017), loquat kernels (Erdal and Taskin 2010), cassava bagasse (Kar et al. 2008; Ray et al. 2008; Ray and Kar 2009; Kar and Ray 2010), orange waste powder, and mango kernels were utilized to produce α-amylase (Djekrif-Dakhmouche et al. 2006; Said et al. 2014). To manufacture diverse products, amylases are used extensively in the food industries such as extraction; clarification of fruit juice; making of starch syrup, moist cakes, chocolate cake, etc.; brewing; and making and baking of digestive aids. Swain et al. (2009) have reported exo-polygalacturonase production from cassava bagasse using *Bacillus subtilis* in solid-state fermentation.

Table 9.4 Microbial enzyme production using fruit and vegetable waste[a]

Enzyme	Waste/substrate	Microorganism used
Amylases	Banana waste	*Bacillus subtilis*
	Cabbage waste	*Pseudomonas* sp.
	Cassava waste	*Bacillus* sp.
	Coconut oil cake	*Aspergillus oryzae*
	Date waste	*Aspergillus niger*
	Loquat kernels	*Penicillium expansum*
	Mango kernel	*Fusarium solani*
	Orange waste	*Streptomyces* sp.
	Potato peel	*Bacillus subtilis*
Cellulases	Banana solid waste	*Cellulomonas carte*, *Bacillus megaterium*, *Penicillium putida*, *Pseudomonas fluorescens*
	Banana waste	*Bacillus* sp.
	Cabbage waste	*Pseudomonas* sp.
	Kinnow waste	*Trichoderma reesei*
	Mango peel	*Aspergillus niger*
	Palm kernel cake and vegetable waste	*Bacillus* sp.
Invertases	Peels of orange, pineapple, pomegranate, and sapota	*Aspergillus flavus*
	Banana peel, pineapple peel	*Aspergillus niger*
Laccases	Apple, grape seeds, kiwifruit waste, orange peel, potato peelings	*Trametes hirsuta*
	Orange waste	*Pleurotus* sp.
Laccases, xylanases	Banana waste	*Aspergillus* spp. *MPS-002*, *Phylostica* spp. *MPS-001*
	Banana skin	*Trametes pubescens*
Lipases	Lemon peel	*Chaloropsis thielarioides*, *Colletotrichum gloeosporioides*
	Coconut cake	*Aspergillus niger*
	Mahua cake	*Lasiodiplodia theobromae*
Pectinases	Apple, strawberry pomace	*Lentinus edodes*
	Pineapple peel	*Penicillium chrysogenum*
	Banana peel, lemon peel, orange peel, and waste	*Bacillus* sp., *Aspergillus niger*, *Penicillium citrinum*
	Waste of banana, cashew apple, grape, pineapple	*Aspergillus foetidus*
Pectinases, cellulases, xylanases	Grape pomace	*Aspergillus awamori*
Tannases	Tamarind seed powder	*Aspergillus niger* ATCC 16620
	Jamun (*Syzygium cumini*) leaves	*Aspergillus ruber*
Xylanases	Apple, pomace, hazelnut, shell, melon peel, palm kernel cake, tamarind seed, orange peel	*Trichoderma harzianum* 1073 D3 *Aspergillus niger*

(continued)

Table 9.4 (continued)

Enzyme	Waste/substrate	Microorganism used
	Pineapple peel powder	*Trichoderma koeningi*
	Watermelon rind, melon peels	*Trichoderma* sp.
	Tomato waste	*Aspergillus awamori*
α-Amylases	Citrus peel	Not mentioned

[a]Source: Ghoshal et al. (2012), Sagar et al. (2018), and Panesar et al. (2016), updated

4 Bioactive from FVWs vs. Health Benefit

The bioactive compounds from some major fruits and their health benefits are discussed.

4.1 Mango

On average, mango fruit comprises seed and kernel 20–60% and 45–75% of whole fruit and seed, respectively (Maisuthisakul and Gordon 2009). A 15–20% of peel is the chief waste produce of mango processing industry (Massibo and He 2008) (Table 9.2).

Numerous polyphenols such as alkyl resorcinol, gallotannins, flavonols, xanthones, and benzophenone and its derivatives have been accounted for in mango fruit waste such as peel and seed kernel (Table 9.3) (Massibo and He 2008; Engels et al. 2011). Many therapeutic prospectives of wastes of mango fruit have been explored, accounting for antidiabetic, antimicrobial, anti-inflammatory, analgesic, immune-modulatory, anti-oxidative, and anticarcinogenic activities (Alok et al. 2013; Shabani and Sayadi 2014).

4.2 Pineapple

According to Banerjee et al. (2018), wastes from pineapple can be classified as pineapple on farm waste (POFW) and pineapple processing waste (PPW). POFW comprises root, stem, and leaf waste in the fields post-harvesting of pineapple. Reported that if pineapple production is 12,000 per acre of land then 2–18 tonnes of pineapples generated 76–92 tonnes of fresh POFW.

4.2.1 Conventional Methods of Utilization of PPW and POFW

Other than composting and dumping, PPW and POFW are traditionally developed as fertilizer and animal feed. Crowns of the pineapple correspond to 25–30% of the waste. When ensiled for 6 months, pineapple peel waste produced 0.67 m^3/kg of biogas. According to Tauseef et al. (2013), Behera and Ray (2020) higher biogas yield was obtained if volatile solids and 65% methane were added, volatile solids were generated from cow dung (of 0.2–0.5 m^3/kg of dry matter). The slurry produced after assimilation of biogas unit could be utilized as soil modifier (Behera and Ray 2020).

4.2.2 Extraction of High-Value Components from PPW and POFW

Additionally in traditional waste utilization methods, PPW and POFW could also be oppressed as substrate to extract valuable components such as carbohydrates and sugars, bromelain enzyme, and TPC (Tables 9.3 and 9.4).

Bromelain (Enzyme) and Its Classification
Bromelain is a combination of protease enzymes and thiol endopeptidases, peroxidases, cellulases, and glucosidases (Maurer 2001) achieved from pineapple. Proteases are the main essential enzymes commercially available with per annum sale of approximately 3 billion US$ (Leary et al. 2009) and found widespread use in food, pharmaceutical, and detergent industry (Feijoo-Siota and Villa 2010). Two main categories of bromelain are available “stem bromelain” (EC 3.4.22.32) and “fruit bromelain” (EC 3.4.22.3) isolated from the stem and from its juice, respectively (Kelly 1996). Bromelain is useful in the leather industry for animal skin softening, pre-tanning, and food and therapeutics. One kilogram of purified bromelain costs about $ 2400 (Ketnawa et al. 2012). After bromelain extraction, the remaining solids can be transformed into precious fuels and chemicals such as lactic acid, bioethanol, xylooligosaccharides, and xylitol (Segui and Fito 2018).

Bromelain as a Food Additive The FDA (Food and Drug Administration, USA) accepted bromelain in 2006 as a safe food additive, commonly comprehensively utilized meat tenderizers next to papain (Banerjee et al. 2018). During cooking or processing the enzyme bromelain denatures, therefore pineapple losses tenderizing effect after heating. Another imperative action of bromelain is as clarifying agent of beer in breweries. Bromelain is also used to stop the browning action of apple juice and cut fruits (Tochi et al. 2008).

Bromelain as a Therapeutic Bromelain stops platelet accumulation, which is the major reason for heart attack (Maurer 2001; Tochi et al. 2008). Bromelain can be used as an antitumor drug, but it cannot destroy cancerous cells entirely, only reduce the number. Still, it has an encouraging effect in breast cancer, melanoma, ovarian cancer, leukemia, and lung carcinoma treatment. It acts as an anti-inflammatory agent, heals asthma, reduces risk of constipation, colonic inflammation, rheumatoid arthritis, and osteoarthritis, relieves gastrointestinal turmoil, diarrhea, vomiting, skin diseases and functions as postoperative precautionary drug for gastrointestinal dysmotility (Maurer 2001; Pavan et al. 2012; Rosenberg et al. 2012). Sancesario et al. (2018) investigated the potential of bromelain during the treatment of Alzheimer's disease and other neurological diseases.

Carbohydrates

PPW and POFW contain free sugars that can be transformed into biofuels (Banerjee et al. 2017) and other bio-based chemicals. The pineapple core includes a considerably higher quantity of glucose and fructose than peels and crowns (Roha et al. 2013). Further simple sugars from PPW and POFW consist of various polysaccharides specifically cellulose and hemicellulose (Guo 2014). It was reported that crude fiber quantity is present in decreasing order in the peels > the crown > core as crude fiber contents are 65 g/100 g of dry sample > 62.5 g/100 g of dry sample > 47.6 g/100 g of dry sample (Pardo et al. 2014).

4.3 Vegetables

During tomato processing, large amounts of skins, pulp, and seeds are recovered, such as a protein isolate recovered from tomato seed waste. It contains various essential amino acids (consisting lysine also) (Sarkar and Kaul 2014). Thus, the tomato seed flour (high-quality protein rich) might be utilized as a component in diverse food arrangements (Ray et al. 2011). By-products isolated from the olive are identified as having excellent antioxidant properties and balanced composition of amino acids, fatty acids, and mineral ions, e.g., sodium, potassium, calcium, and magnesium. They are the possible component for skincare cosmetic products mainly as a natural moisturizing factor. Tables 9.2 and 9.3 showed the recovered by-products from the fruit and vegetable industries.

5 Food Additives from FVWs

Novel food means innovative, highly featured food in color, flavor, taste, and texture. When raspberry marc extract (2%) was incorporated in mixed fruit purees, total phenolic content was elevated 2–three fold, therefore improving the functional properties of products (Bobinaitė et al. 2016). During pumpkin (var. Muscovy) waste processing, bioactive compounds contain antioxidant, antimicrobial, and pro-health properties (Saavedra et al. 2015). Incorporating prebiotic fiber such as inulin, oligofructose, and apple fiber causes considerable development of antioxidant activity and flourishing protection of the sensory attributes of strawberry juice (Cassani et al. 2016). Incorporation of fruit pomace in functional food research, mainly in bakery commodities, may supply efficiently to healthier features alongside numerous lifestyle disorders. Sudha et al. (2016) incorporated apple pomace to improve the bioactivity. Blueberry pomace flour may be used in the production of fermented beverage. Reque et al. (2014) illustrated a superior antioxidant capability of blueberry compared to other fruit juices. The pomace confirmed elevated antioxidant activity, whereas the dried blueberry pomace flour reduced to 46% from 66% of their raw materials, respectively. The replacement of conventional flour for making biscuits and cereal bars with plant waste flour (20 to 35%) was done. Biscuits with 35% pomace flour had a considerably superior quantity of fiber (57–118%) and mineral compounds (25–37%), compared to biscuits supplemented by 20% by-product flour (Ferreira et al. 2015). Waghmare and Arya studied the outcome of the diverse intensity of pulverized fruit by-products *thepla* containing 9% apple pomace, 9% papaya peels, and 3% watermelon rinds on glycemic index, which cause a diminution of the glycemic index from 68 to 55 (control) in *thepla*. As compared to other fruit and vegetable by-products, salad waste showed high water retention.

Plazzotta et al. (2017) claimed salad waste as a resource of water and valuable nutraceuticals, polyphenols, and fiber. Therefore, it is also feasible to utilize the pomace from apple to manufacture gluten-free products (Parra et al. 2015). In addition, apple fiber may be utilized for manufacturing low-calorie foodstuff due to its good ability to absorb water (Sharma et al. 2016).

6 Animal Feed

The most extensively utilized and simple process applied in the execution of waste from fruit and vegetable industry can be utilized for making farm animal feed. However, as the water quantity of plant waste is excessively high when incorporating it into feed formulations without pre-treatment, it is essential to dry initially before preparation using pulse combustion drying, oven, and microwave.

7 Conclusion and Future Perspectives

This chapter focused on the generation, type, and nature of the waste derived from fruits and vegetables. It is also considered as the selective bioactive composite like dietary fibers, flavor, phenolics, organic acids, and enzymes present in FVWs. Isolation methods of these bioactive composites by traditional and non-traditional processes are illustrated scientifically. Extracted bioactive compounds can be utilized in chemical, food, pharmaceuticals, cosmetics industries, and functional food research.

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Chapter 10
Microbial Enzymes and Organic Acids Production from Vegetable and Fruit Wastes and Their Applications

Poonam Kumari, Akshita Mehta, Rutika Sehgal, Ramesh C. Ray, and Reena Gupta

Abstract Food and vegetable waste management has become a major economic and environmental challenge. The fruit and vegetable wastes contain a variety of bioactive substances such as dietary fibers, phenolic compounds, enzymes, flavors, and organic acids. The significantly large amount of fruit and vegetable waste contains various by-products which are very beneficial for various industries. A vast range of industrial enzymes can be produced from various food and vegetable wastes. Extracted enzymes and organic acid can be used in food, pharmaceutical, cosmetic, and chemical industries and food research. This chapter focuses mainly on the characterization of different types of fruit and vegetable wastes and optimization of fermentation parameters to produce various industrially important enzymes such as amylase, cellulase, pectinase, protease, and phytase and organic acids such as acetic acid, lactic acid, etc., using a wide range of microorganisms isolated from different food wastes. In addition, the advances in genetic engineering to improve microbial strain to enhance the enzymes and organic acids have been discussed.

Keywords Bioactive compounds · Organic acid · Fermentation · Genetic engineering · Enzyme · Solid-state fermentation · Submerged fermentation

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1 Introduction

Agricultural waste refers to the undesired materials or by-products produced by various agricultural processes, which account for more than 30% of global agricultural output (Ashworth et al. 2009). Because it reduces carbon dioxide emissions, recycling organic wastes through the bioconversion process has become an important part of environmental preservation. According to the Food and Agriculture Organization (FAO), losses and wastes in vegetables and fruits are the highest of all food types, accounting for up to 60% of the total production (FAO 2017). Fruit and vegetable processing operations generate large amounts of waste as by-products, accounting for around 25–30% of the whole commodity group. The waste comprises seed, skin, rind, and pomace containing abundant source of potentially valuable bioactive compounds, such as carotenoids, anthocyanins, polyphenols, dietary fibers, vitamins, enzymes, organic acids, minerals, and bio-oils. The use of waste to produce a variety of vital bioactive components is a crucial step toward long-term sustainability. Fruits and vegetables are essential components of our diet and human lives. As a result of the expanding global population and changing dietary patterns (Schieber et al. 2001; Vilariño et al. 2017), demand for such vital food commodities has increased dramatically. Citrus accounts for 124.73 million metric tons (MMT), bananas for 114.08 MMT, apples for 84.63 MMT, grapes for 74.49 MMT, mangoes for 45.22 MMT, and pineapples for 25.43 MMT of global fruit production (FAO 2017). Potatoes (3820.00 MMT), tomatoes (171.00 MMT), cabbages and other brassicas (71.77 MMT), carrots and turnips (38.83 MMT), cauliflower and broccoli (24.17 MMT), and peas (17.42 MMT) are among the vegetables produced (FAO 2017). Reducing the pollution and its related issue has boosted the search for "clean technologies" that have to be used to produce commodities applicable to chemical, energy, and food industries. It has been reported that waste materials can be used as substrates for microbial production to produce cellular proteins, organic acids, mushrooms, biologically essential secondary metabolites, enzymes, prebiotics, oligosaccharides, and fermentable sugars for second-generation ethanol production (Sanchez 2009). Filamentous fungi are the most notable producers of enzymes involved in the lignocellulosic material breakdown. The search for novel strains with high enzyme production potential is crucial in biotechnological research. Proteases, lipases, cellulases, xylanases, ligninases, and organic acids such as acetic acid, succinic acid, lactic acid, and citric acid are important microbial enzymes having potential applications in a variety of biotechnology processes.

2 Waste Management Strategies

Due to expanding population and changing eating preferences, fruit and vegetable production has increased considerably in recent years, with more people adopting vegetarian diets (Schieber et al. 2001; Vilariño et al. 2017; Sagar et al. 2018).

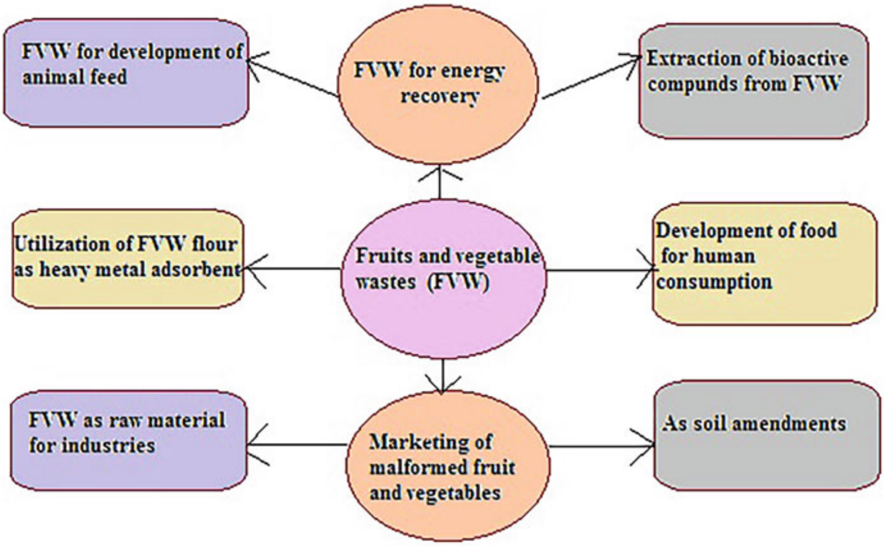

Fig. 10.1 Fruit and vegetable waste management strategies

Increased agricultural production, along with improper handling of fruits and vegetables at wholesalers' and retailers' outlets, as well as consumers' carefree attitudes toward wastage, have resulted in massive losses and waste of essential agri-food commodities. Fruit and vegetable wastes (FVWs) are a serious environmental hazard. Most of them are disposed of in landfills or straight into aquatic bodies like rivers (Wadhwa et al. 2013). Because they are highly perishable due to high moisture content, this causes serious environmental pollution and microbial contamination (Banerjee et al. 2017; Plazzotta et al. 2017; Pham Van et al. 2018; Coman et al. 2019; Bas-Bellver et al. 2020). The FVW management strategies have improved in recent years. There are many sustainable methods for dealing with FVWs, including reusing them as a soil amendment or animal feed, extracting beneficial compounds, and more (Arvanitoyannis et al. 2008; Prokopov 2014; Plazzotta et al. 2017; Coman et al. 2019; Peng et al. 2019; Salehiyoun et al. 2019). FVW and by-products have a lot of reuse, recycling, and recovery potential (Fig. 10.1).

3 Enzymes from Fruit and Vegetable Wastes

Enzymes are proteins that act as biocatalysts, accelerating biological reactions in living organisms. Because they appear to be more efficient, selective, and less expensive than chemical catalysis, they can be used in various biotechnological applications (Binod et al. 2013). In numerous production domains such as food, textile, detergent manufacture, washing, animal feeding, cosmetics, biofuel, and fine chemical production, enzymes are used in over 500 products and 150 industrial processes (Kumar et al. 2014). In 2015, the enzyme industry was worth around $8 billion, and forecasts suggest that it will continue to increase rapidly until 2024 when it would be worth $17 billion (Grand View Research 2016). The need for more sustainable products, such as enzymatically produced biofuels and functional foods with biological properties obtained from catalytic processes, has increased (Kumar et al. 2014; Prado et al. 2018). Lipases are the biocatalysts with the most promising market growth prospects, as lipase production is expected to grow almost 600 million dollars per year by 2020. It would mostly occur as a result of rising demand in Asia and Latin America for health, biofuel, and food production (Table 10.1).

3.1 Protease

Proteases (EC 3.4.21.112) account for nearly 60% of the total enzyme sales (Godfrey et al. 1996) because of their diversified applications in various fields, such as such as dry cleaning, detergents, meat processing, cheese making, silver recovery from photographic film, production of digestive and specific medical treatments of virulent inflammation wounds, and waste management (Nout et al. 1990; Mohapatra et al. 2003). Some fungi such as *Aspergillus*, *Rhizopus*, and *Penicillium* and species of bacteria of genus *Bacillus* have been reported as the active producers of proteases (Chutmanop et al. 2008; Khosravi-Darani et al. 2008; Jamrath et al. 2012). High protease activity was achieved at pH 10 at 37 °C, and the enzyme was reported to be thermostable, indicating its possible utilization in the food industry (Khosravi-Darani et al. 2008). Afify et al. (2011) investigated protease production from potato waste in a submerged fermentation system using the yeast, *Saccharomyces cerevisiae*. They also studied the utilization of residual solid waste as a biofertilizer for plant development. Madhumithah et al. (2011) presented a novel and economic approach for the bioconversion of vegetable wastes to produce protease. They used different vegetable wastes such as potato, pumpkin, cauliflower, cabbage, and brinjal as substrates in the solid-state fermentation (SSF) for protease production using *A. niger* (as producer microorganism).

3.2 Amylase

Alpha amylases (EC 3.2.1.1, endo-1,4-D-glucanglucanohydrolase) are a class of enzymes that cleave 1,4 linkage between adjacent glucose subunits in polysaccharides at random, releasing short-chain oligomers and limiting dextrins. Alpha amylases are used in a variety of activities, including the production of detergents, bread, beer textiles, paper, pulp, and pharmaceuticals (Sahnoun et al. 2015). Amylase breaks down starch molecules into dextrin, maltose, and glucose units. Amylases

Table 10.1 Demonstration of microbial enzyme production from fruit and vegetable wastes

Sr. no	Enzyme	Substrate	Microorganism	References
1	Cellulase	Banana peel Mango peel Apple pomace	*Trichoderma viride* *Trichoderma reesei* *Trichoderma* sp.	Hai-Yan Sun et al. (2011) Dhillon et al. (2012)
2	Xylanase	Grape pomace Banana peel	*Aspergillus awamori* *Aspergillus fumigatus*	Botella et al. (2007) Zehra et al. (2020)
3	Pectinase	Citrus peel Decomposing passion fruit peel Rotten orange	*Bacillus* sp. *Aspergillus oryzae*	Wang et al. (2020) Biz et al. (2016)
		Mango waste Citrus fruit peel	*Aspergillus niger*	Darah et al. (2013) and Mahmoodi et al. (2017)
		Rotten vegetable waste Mosambi/lemon peel Banana peel	*Fusarium* sp.	Reddy et al. (2015)
			Aspergillus niger	Rehman et al. (2014) Dange et al. (2018)
			Bacillus licheniformis *A. oryzae*	Sethi et al. (2016)
			Aspergillus terreus	
4	Invertase	Pineapple peel Pomegranate peel Papaya peel Orange peel	*A. niger* *Cladosporium* sp. *Aspergillus* sp. *A. niger*	Oyedeji et al. (2017) Uma et al. (2012) Chelliappan et al. (2013) Mashetty and Biradar (2019)
5	Amylase	Banana waste Banana Pomegranate Grapes Orange peel Banana peel	*Bacillus* sp. *Bacillus subtilis*	Krishna and Chandrasekaran (1996) Kavitha (2018)
			Lactobacillus *Bacillus amyloliquefaciens* *A. niger*	Padmavati et al. (2018) Uygut et al. (2018) Oshoma et al. (2019)
6	Protease	Date waste Potato waste Cauliflower Pumpkin Brinjal Cabbage Banana Banana/grapes	*Bacillus* sp. *Saccharomyces cerevisiae* *A. niger*	Khosravi-Darani et al. (2008) Afify et al. (2011) Madhumithah et al. (2011)
			B. subtilis	Kavitha (2018)
7	Glucoamylase	Potatoes	*A. awamori*	Kiran et al. (2014)

(continued)

Table 10.1 (continued)

Sr. no	Enzyme	Substrate	Microorganism	References
8	Polygalacturonase	Apple peel/orange peel Citrus peel Orange peel Apple peel/banana peel	*Aspergillus nomius*	Ketipally et al. (2019)
			Penicillium chrysogenum *A. awamori*	Zaslona et al. (2015) Padma et al. (2012)

are important in industry because of their commercial applications in starch liquefaction, paper, textile fabric design, preparing starch coatings of paints, removing wallpaper, brewing, sugar induction by the production of sugar syrups, pharmaceuticals, and the preparation of cold water dispersible laundry detergent (Tanyilidizi et al. 2005). Currently, amylase production accounts for up to 65 percent of the global enzyme market and is steadily rising (Abdullah et al. 2014). Previously, banana waste (pre-treated banana fruit stalk by autoclaving at 121 °C for 60 min) was used as a substrate for *Bacillus subtilis* CBTK 106 to produce high titers of α-amylase (a minimum of 5,345,000 U/mg/min) (Krishna and Chandrasekaran 1996). The *Bacillus* genus is well-known for producing α-amylase (Swain and Ray 2007). Several *Bacillus* strains are identified and evaluated for amylase production, including *B. stearothermophilus*, *B. subtilis*, *B. cereus*, *B. licheniformis*, and *B. amyloliquefaciens* (Sivaramakrishnan et al. 2006). Some *Bacillus* strains are involved in the breakdown of raw starch (Demirkan et al. 2005). Many people are still looking for the best production with distinctive industrial qualities. Still there is always a search for strains with high level of production having unique properties favorable for industrial use. The use of cutting-edge techniques like induced mutation and gene cloning, as well as optimizing culture conditions, could help improve enzyme production. The use of these waste materials provides a low-cost medium for amylase synthesis while also addressing the issue of environmental pollution. Kavitha (2018) reported the production of amylase and protease by *B. subtilis* using agro-waste substrate such as fruit peel (banana, pomegranate, and grapes) by solid-state fermentation. The most common FVW used to produce amylases are banana peel (Oshoma et al. 2019) and orange peel (Uygut et al. 2018).

3.3 Cellulase

Endoglucanase (E.C.3.2.1.4), exoglucanase (E.C.3.2.1.176), cellobiohydrolase (E.C. 3.2.1.91), and glucosidase (E.C.3.2.1.21) are the key enzymes involved in the depolymerization of cellulose into its component glucose molecule (Behera and Ray 2016). They belong to the glycoside hydrolase family and are responsible for the cleavage of glycosidic bonds (Juturu et al. 2014). Cellulases are enzymes of great commercial importance. Cellulase enzymes are mainly used in bioethanol production (Singhania et al. 2014). Besides bioethanol, cellulase has application in different industries such as bread, brewing, textiles, detergents, paper, and pulp sectors (Ferreira et al. 2014). A wide range of bacterial and fungal species produce cellulase enzymes. *Trichoderma* spp. is the most commonly used fungi to produce cellulase enzymes (Pakarinen et al. 2014). Other than *Trichoderma* sp., *Schizophyllum commune*, *Melanocarpus* sp., *Aspergillus* sp., *Penicillium* sp., and *Fusarium* sp. are also used to produce cellulase enzyme (Juturu et al. 2014). The development of cheaper methods to create cellulases has been a significant focus of researchers over the last two decades due to its impact on the economics of bioethanol production (Klein-Marcuschamer et al. 2012). Several experiments have been conducted to test if lignocellulosic food waste may be used as a carbon source for *Trichoderma viride* GIM3.0010 to produce cellulase in SSF. According to Hai-Yan Sun et al. (2011), banana peel provided the nutrients required for cell development and cellulase synthesis. Cellulase is used in the textile industry for the production of detergents and also in the food industry (Imran et al. 2016) and industrial biotechnology (Bajaj and Mahajan 2019). Taher et al. (2017) used potato peel for the production of cellulase.

3.4 Pectinase

Pectinolytic enzymes are a family of enzymes that break down pectic materials. Pectin is a complex polymer found in the middle lamella of plant cell wall. Multiple units of D-galacturonic acid are joined together by a (1, 4) glycosidic bond to form pectin (Priya and Sashi 2014). Higher plants (Nighojkar et al. 1994; Jolie et al. 2010) and microorganisms, such as bacteria and fungi, have been found to contain pectinolytic enzymes (Uzuner et al. 2015; Patidar et al. 2016; Rebello et al. 2017). Pectin methylesterase (pectinesterase; EC: 3.1.1.11), pectinase (polygalacturonase; EC: 3.1.1.15), and pectin lyase (EC: 4.2.2.10) are three important enzymes that break down pectin to release galacturonic acids and associated oligomers (Swain and Ray 2010; Combo et al. 2012). Microorganisms have a lot of potentials when it comes to synthesizing pectinase in nature. Pectinases are well-known for their enormous potential in a variety of fields. Softening of fruits, juice extraction and clarification, gel preparation, food manufacture, retting of textile fibers, olive oil extraction, protoplast isolation, and other processes rely on pectin methylesterase and endo-polygalacturonase (Kashyap et al. 2001; Jayani et al. 2005; Kohli and Gupta 2015). Galacturonic acid, which is generated by pectinolytic enzymes, is used in various sectors, primarily pharmaceuticals. It is utilized as an acidic agent in the food industry and as a washing powder agent in the chemical industry to make vitamin C. (Molnar et al. 2009; Burana-Osot et al. 2010). Bacterial isolates such as *B. subtilis* SAV-21 (Kaur and Gupta 2017) and *B. licheniformis* (Pervez et al. 2017) have recently been shown to generate pectinase in SSF. Pereira et al. (2017) used the edible *Pleurotus sajor-caju* fungus to produce pectinase in SSF. *S. cerevisiae*, a yeast isolated from FVW, has been used to produce pectinase using SSF (Poondla et al. 2016). Wang et al. (2020) isolated seven bacteria from orange peel and tested their ability to produce pectinase. In comparison to the other organisms, *Bacillus* sp. had the highest enzyme activity. Pectinase is extensively employed in the production of wine and fruit juices (New et al. 2018; Nighojkar et al. 2019). It's also used to extract pigments and essential oils from FVWs (Munde et al. 2017) (Sagar et al. 2018; Castilho et al. 2000). Additionally, it is also used in the production of high-quality paper (Ahlawat et al. 2008; Rebello et al. 2017), coffee and tea fermentation, and the treatment of pectic waste (Kashyap et al. 2001; Rebello et al. 2017). Citrus waste peel (Ahmed et al. 2016), banana peel (Sethi et al. 2016), mango peel (Kuvvet et al. 2019), sugarcane bagasse (Biz et al. 2016), and pineapple stem (Kuvvet et al. 2019) have all been used to make microbial pectinases (Kavuthodi and Sebastian 2018).

3.5 Invertase

Invertase (EC.3.2.1.26), also known as fructofuranosidase, is a glycoprotein that catalyzes the hydrolysis of sucrose into glucose (dextrose) and fructose. At a pH of 4.5 and a temperature of 55 °C, the invertase is at its most active. *S. cerevisiae* is the most common microorganism utilized to make invertase enzymes (Neumann et al. 1967). Invertase is a protein that aids in synthesizing invert sugar via acid hydrolysis. The conversion of sucrose to invert sugar is 50% when hydrolyzed in acid. When invertase is used, sucrose is completely inverted without forming any contaminants (Kulshrestha et al. 2013). Because invertase is a commercially expensive enzyme, numerous researchers have attempted to produce it with low-cost carbon sources. For example, Hang et al. (1995) investigated the use of apple pomace as a carbon source for the synthesis of invertase from *Aspergillus foetidus* NRRL 337. On the other hand, Rashad et al. (2009) employed red carrot jam processing residue as an SSF medium to characterize invertase produced by *S. cerevisiae* NRRL Y-12632. Orange, pineapple, and pomegranate peel wastes have been investigated and proved to be excellent carbon source alternatives for invertase production using a variety of microbial species (Alegre et al. 2009; Uma et al. 2012; Veana et al. 2014). Invert sugar, artificial sweeteners, chocolates, lactic acid, glycerol, sweets, and confectionery are all made using invertase (Sagar et al. 2018; Veana et al. 2014; Mashetty et al. 2019). The presence of sucrose, lactose, and fructose is also required to synthesize this enzyme using FVW (Sagar et al. 2018). FVW that has been so far used is pineapple peel (Oyedeji et al. 2017). Invertase is used in the pharmaceutical sector and to extend the shelf-life of products in the food industry (Kumar and Kesavapillai 2012; Panda et al. 2016).

3.6 Phytase

Phytase (myo-inositol hexakisphosphate phosphohydrolase, EC 3.1.3.8) is a type of phosphatase enzyme that catalyzes the hydrolysis of phytic acid (myo-inositol hexakisphosphate). Phytic acids are an indigestible form of phosphorus that is found in many plant tissues, especially in grains and oil seeds, and are broken down by phyrases into usable form of inorganic phosphorus. Phytases are widely distributed and can be produced by various living organisms, including plants, animals and microorganisms (Yao et al. 2011). Histidine acid phosphatases (HAPs), isolated from filamentous fungi, bacteria, yeasts, and plants, are the first and most widely researched category of phytases based on their catalytic function and structure (Mullaney et al. 2000). Fungi produce phytase at different temperatures and pH levels, which vary from neutral to acidic (pH 1.0–6.0) to alkaline (pH 8.0–14.0). (Yao et al. 2011; Singh et al. 2014). However, *Aspergillus niger* is the strain most frequently used to make phytase. In addition, phytases have been used as a soil amendment and plant growth promoter, as well as in the semi-synthesis of peroxidase used in the paper and pulp industries (Singh et al. 2011). Several studies of SSF have been performed using filamentous fungi for phytase production, such as *Aspergillus flavus*, *A. ficuum*, *A. niger*, *A. tubingensis*, *Ganoderma stipitatum*, *Grifola frondosa*, *Mucor racemosus*, *Penicillium purpurogenum*, *Rhizopus oligosporus*, *R. oryzae*, *Schizophyllum commune*, *Thermomyces lanuginosus*, and *Trametes versicolor*. Rice bran, wheat bran, wheat straw, citrus peels, soybean meal, oil cakes, maize cobs, and coconut oil cakes are some of the substrates commonly utilized for phytase production (Sabu et al. 2002). Another study employed orange peel flour to produce phytase with *Klebsiella* sp. under submerged fermentation cultivation conditions; the phytase was thermo- and acid-stable (Mittal et al. 2012).

3.7 Tannase

Tannin acyl hydrolase (EC.3.1.1.20), often known as tannase, is engaged in the biodegradation of tannins into gallic acid and glucose. Many investigations on tannase synthesis use fungi or bacterial species and agricultural residue as a substrate. An intriguing study was conducted on tannase production by *Aspergillus* and *Penicillium* species employing leaves and agro-industrial waste, such as Barbados cherry and Mangaba fruit, as substrate in solid-state fermentation (Lima et al. 2014). The tannase enzyme is also widely employed in the food industry to generate key products. Tannase is used to clear fruit liquids and beer, as well as to make colors, gallic acid, and instant tea (Ramirez-Coronel et al. 2003; Banerjee et al. 2005). Tamarind seed powder and palm kernel cake were used by *A. niger* to make tannase. Kumar et al. (2007) used *Aspergillus ruber* to produce tannase from tannin-rich waste such as jamun leaves (*Syzygium cumini*), amla leaves (*Phyllanthus emblica*), ber leaves (*Ziziphus mauritiana*), and others. Likewise, *Penicillium atramentosum* generated extracellular tannase using ber, amla, and jamun leaves as a carbon source as well as a substrate during submerged fermentation (SmF). Among them, amla (2% w/v) produced the highest quantity (32.8 U/mL) of tannase (Selwal et al. 2012). Varadharajan et al. (2016) investigated different horticultural wastes for the production of tannase by *A. oryzae* under SmF.

4 Production of Organic Acids from Fruit and Vegetable Waste

Organic acids are chemical building blocks that can be produced through microbial fermentation. Organic acids are produced commercially by microorganisms such as bacterial (*Lactobacillus* spp.) and fungal (*Aspergillus* spp.) species in a variety of industries and processing units such as food processing, nutrition, and feed industries, pharmaceuticals, oil and gas stimulation units, and so on (Sauer et al. 2008) (Table 10.2).

Table 10.2 Demonstration of organic acid production from fruit and vegetable waste

Sr. no	Organic acid	Substrate	Microorganism	References
1	Citric acid	Apple pomace Pineapple waste Banana peel	*Aspergillus niger* *Yarrowia lipolytica* *A. niger*	Shojaosadati et al. (2002) Imandi et al. (2008) and Roda et al. (2014) Karthikeyan et al. (2010)
2	Acetic acid	Pineapple peel	*Saccharomyces cerevisiae* and *Acetobacter rancens*	Singh and Singh (2007)
		Pineapple peel	*S. cerevisiae* and *Acetobacter*	Raji et al. (2012)
3	Lactic acid	Mango peel Orange peel	*Lacticaseibacillus* *Lactobacillus delbrueckii*	Mudaliyar et al. (2012)
		Kimchi cabbage	*Latilactobacillus sakei*	Kim et al. (2018)
4	Succinic acid	Banana/orange Watermelon/pineapple	*A. niger* *Rhizopus oryzae*	Dessie et al. (2018)
5	Ferulic acid	Pineapple peels Pineapple crown leaves	*A. niger* I-1472	Tang and Hassan (2020)

4.1 Citric Acid

Citric acid is a carboxylic acid commonly used in food and pharmaceuticals (Panda et al. 2020). Citric acid is produced worldwide either from citrus fruits or through fermentation using the fungus *A. niger*, *A. flavus*, and other *Aspergillus* species (Mathew et al. 2020). Chemical synthesis can also be used to make citric acid. On the other hand, citric acid is mostly produced by SSF employing *A. niger* from different carbon sources such as agro-industrial waste. Citric acid synthesis by fermentation has been extensively researched to make use of agricultural by-products. Because of their high nutrient content, banana peels were chosen as a prospective alternate substrate for citric acid synthesis (Alagarsamy et al. 2010). For citric acid production, apple pomace and peanut shell were used as substrates in SSF. A consortium of *Aspergillus ornatus* and *Alternaria alternate* was used as the microbial inoculant (Ali et al. 2016). Citric acid is a widely utilized multifunctional organic acid that is readily available (Swain et al. 2012). The global demand for citric acid is about 6.08×10^5 tons per year. Its uses are increasing day by day. Citric acid production from the different waste substrates such as banana peels, coconut husk, and rice straw using *A. niger* and *A. flavus* was reported (Sharma et al. 2020).

4.2 Lactic Acid

Lactic acid is important in the carboxylic acid group because it has various food and non-food industry applications. It is mainly utilized as an acidulant and preservative in food items (Rodríguez-Coute 2008). The cost of raw materials is the most significant issue in lactic acid production. Using the SSF approach, John et al. (2006) reported that *Lactobacillus delbrueckii* can convert 99% of the total sugars in cassava bagasse into lactic acid under optimal circumstances. Lactic acid is produced by a variety of microorganisms using fruit and vegetable by-products. Using potato peel, sweet corn, mango, orange, green peas, and cassava residue as substrates, *Lacticaseibacillus casei*, *Lactobacillus delbrueckii*, and *Lactiplantibacillus plantarum* have been employed to produce lactic acid (Ray et al. 2008; Mudaliyar et al. 2012; Jawad et al. 2013; Panda et al. 2016). Kim et al. (2018) reported the production of organic acid from kimchi cabbage waste using lactic acid bacteria. They use *Latilactobacillus sakei* subsp. *sakei* and *Latilactobacillus carvatus* that could efficiently produce lactic acid, fumaric acid, and acetic acid from kimchi cabbage waste.

4.3 Acetic Acid

The most important carboxylic acid is acetic acid (CH_3COOH), commonly known as ethanoic acid. Vinegar is a weak solution of acetic acid made from the fermentation and oxidation of natural sugars. Acetic acid is used to make metal acetates, which are used in printing processes. Other examples are vinyl lactate, which is used to make plastics; cellulose acetate, which is used to make photographic films and textiles; and volatile organic esters, which are widely used as solvents for resins, paints, and lacquers. *Acetobacter* species have been isolated from a variety of natural sources, including grape, date, and palm resources, coconut, fruits, and particularly damaged fruits (Kadere et al. 2008). They have been used to make a variety of vinegars from a variety of substrates, including sugarcane (Kocher et al. 2006). The manufacturing of vinegar from fermented pineapple by-products (peels) was described by Chalchisa et al. (2021). The vinegar was made by fermenting pineapple peels with three different acetic acid bacteria strains, including *Propionibacterium acidipropionici*, *Pantoea agglomerans*, and *Pantoea dispersa*. For the manufacturing of vinegar from pineapple peels, they introduce a new sort of sour acid bacteria strain. Roda et al. (2014) also discovered that pineapple trash might be used to make acetic acid. The acetic acid produced was also employed as a wound treatment, a food preservative, and a disinfectant.

5 Genetic Modification of Microorganism

The use of genetically modified microorganisms (GMM) for industrial enzyme and organic acid synthesis is useful since it permits the combination of appropriate production sources to generate the required commodity. For example, if a pathogenic strain produces a native enzyme unsuitable for industrial uses, the enzyme can be generated by a different organism that is more acceptable for food safety. In addition, if undesired secondary metabolites, such as toxins, are created, genetic alterations can be employed to prevent their expression by deleting native genes (Hjort et al. 2007).

5.1 Increased Gene Expression

An effective gene expression of the interested gene is critical for obtaining a high enzyme production. Multiple integrations are the most often utilized methods for increasing the expression yield (Lopes et al. 1989). Various strategies can be used to achieve this objective, including (i) using a large amount of DNA during the transformation, (ii) applying a strong antibiotic pressure that can be achieved by using a high antibiotic concentration or a weak promoter for the selection marker, or

(iii) using two copies of the gene of interest in bidirectional expression vectors or integrating several expression constructs expressing distinct selection markers simultaneously or sequentially (Rieder et al. 2015). On the other hand, the incorporation of numerous copies can cause strain instability that can be a concern in industrial-scale production where a long-term cultivation technique is necessary. The post- transformational vector amplification (PTVA) approach that uses escalating antibiotic concentrations is an example of applying antibiotic pressure to select bacteria with multiple insertions (Sunga et al. 2008). The strength of the promoter is another essential component in enhancing gene expression. Constitutive promoters are distinguished from tunable promoters by a collection of activators and repressors that regulate their expression. Constitutive promoters regulate the expression of basA genes and are expressed independently of the transcription factors generated by the environment. The *amyL* (*Bacillus licheniformis* α-amylase) and *amyM* (*Bacillus stearothermophilus* maltogenic amylase) genes are frequently utilized as promoters in *Bacillus* species.

5.2 *Non-targeted Mutagenesis*

Microorganisms were genetically manipulated for decades prior to the advent of modern biotechnology by applying random mutagenesis generated by chemicals or UV irradiation. Traditional mutagenesis and selection approaches to modification are non-targeted. They induce random DNA alterations, followed by a lengthy screening process to choose microbes that produce more of a certain enzyme or exhibit a desired phenotypic characteristic. It is impossible to predict the genetic makeup of bacteria created through random mutagenesis. Even high-throughput DNA sequencing available today may not always provide a perfect understanding of all DNA changes or their repercussions.

5.3 *Protein Engineering*

Protein engineering is frequently used to improve enzyme functioning (or other proteins). This may be used to boost catalytic activity. Still, it is more commonly used to tune the enzyme to work better in application conditions that may include temperature, pH, or salt concentrations that are considerably beyond the enzyme's optimal range. Baking amylases, for example, can be modified to survive higher oven temperatures for longer. Before the enzyme is inactivated in the baking process, a lower initial enzyme concentration can be used to obtain the exact number of catalytic reactions. Effective protein engineering frequently entails the synthesis of many variants by genetic engineering of the producer organisms (particularly when expression levels need to be increased).

5.4 Gene and Genome Editing

CRISPR is the most widely used gene editing method today. CRISPR is a groundbreaking technique that uses specialized proteins inspired by nature and designed by scientists to cut and paste DNA with pinpoint accuracy. There are three types of gene editing proteins: zinc fingers, TALENs, and CRISPR-Cas. Because of its elegant design and straightforward cell delivery, CRISPR-Cas is now being utilized to heal genetic illnesses, cultivate climate-resilient crops, and develop designer materials, foods, and pharmaceuticals. Clustered regularly interspaced palindromic repeats (CRISPR) are pieces of DNA that developed in certain bacteria as an ancient defense system against viral incursions (Barrangou et al. 2007). CRISPR-Cas is a system that consists of enzymes (Cas proteins) and genetic guides (CRISPR sequences) that work together to identify and alter DNA.

6 Conclusion and Future Perspectives

The conversion of waste into bioproducts is critical for improving the efficiency and sustainability of the food supply chain. Because these wastes can be used to make colors, flavors, cosmetics, polysaccharides, biopesticides, plant growth regulators, biofuels, and bio-oils, they are a valuable resource. Furthermore, the production of various enzymes, organic acids, and other biotechnological products could be incorporated into various biotechnological industries, such as biorefineries, allowing for the creation of a variety of products while increasing the profitability and sustainability of the processing..

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Chapter 11
Fruit and Vegetable Peel Waste: Applications in Food and Environmental Industries

Harsh Kumar, Kanchan Bhardwaj, Daljeet Singh Dhanjal, Ruchi Sharma, Eugenie Nepovimova, Rachna Verma, Dinesh Kumar, and Kamil Kuča

Abstract Reduction of food waste by extensively using raw sources builds good impact on the climate, environment, and food security. Fruits and vegetables are the commodities of horticultural crops that are commonly used. Thus, the waste generated during processing can be proclaimed as a valuable by-product if extensive technological interventions are used to improve the value of successive goods to balance the cost of processing. Fruit and vegetable wastes have great potential for bioconversion into valuable products with biotechnological, biocontrol, bioenergy, and industrial applications. These wastes could serve as a source of edible coating, fat mimetics, fortified probiotics, natural pigment, and volatile compounds in the food industry. Additionally, these wastes can also be used for synthesizing green carbon dots, biochar, and biosorbents that have environmental applications. The utilization of these fruit and vegetable wastes for generating valuable products is a foundation step towards sustainable development. The current chapter discusses the

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valuable products that can be obtained by bioconversion of waste of fruits and vegetables by enlisting their application in both food and environmental sectors.

Keywords Food · Fruits · Vegetable · Food industry · Environmental sector

1 Introduction

In the European Union (EU), around 89 million tons of food waste are produced per year, a figure that is projected to quadruple in the next few years. In India as per the Food and Agriculture Organization (FAO), about 30–40% of produced food gets wasted (Plazzotta et al. 2017; Kumar et al. 2020a). Other sources, such as the Food Corporation of India, have proclaimed a 10% to 15% loss during production. According to the Ministry of Food Processing Industries (MFPI), India, the vegetable and fruit losses are projected to be 21,000,000 and 12,000,000 tons, respectively, with a loss of gross food value and produced waste of 10.6 billion USD (Kumar et al. 2020a). Fruit and vegetable waste (FVW) is a broader term that refers to indigestible pieces of fruits and vegetables that are discarded at various phases of the supply chain such as handling, collection, shipping, and further processing (Chang et al. 2006). The term FVW is defined as loss of vegetable and fruit other than waste, according to the definition stated above. FVW can be generated at various points in the food supply chain, from field to market, including pre- and postconsumer periods equally (Panda et al. 2016, 2018).

FVW contains many phytochemical constituents, which have been reported for their phenolic compounds, dietary fibers, and extraction of other phytochemical compounds (Galanakis 2012). Essential phytochemicals and nutrients are found in ample amount in the seeds, peels, and other components of generally consumed vegetables and fruits (Rudra et al. 2015). Avocado skin, grape skin, lemon peel, jackfruit seeds, and mango skin, for example, have 15% higher phenolic concentrations in contrast to fruit pulp (Gorinstein et al. 2001; Soong and Barlow 2004). FVWs can be used to extract and obtain bioactive compounds for use in the food, clothing, cosmetics, and pharmaceutical industries (Fig. 11.1). Since certain wastes come from horticultural products, they are currently deemed unimportant. Thus, the proper application will address environmental concerns and serve as a long-term strategy for improving health by enriched foods containing health-promoting substances (Sagar et al. 2018). The current chapter summarizes advanced developments and techniques of using waste generated by vegetables and fruits peel as a valuable, potential product of the future.

2 Food Industry

Fruits and vegetables are rich sources of various phytochemicals, bioactive compounds, and dietary fibers. But these important constituents are also present in fruit and vegetable wastes like peels, seeds, and other leftover parts of both fruits and

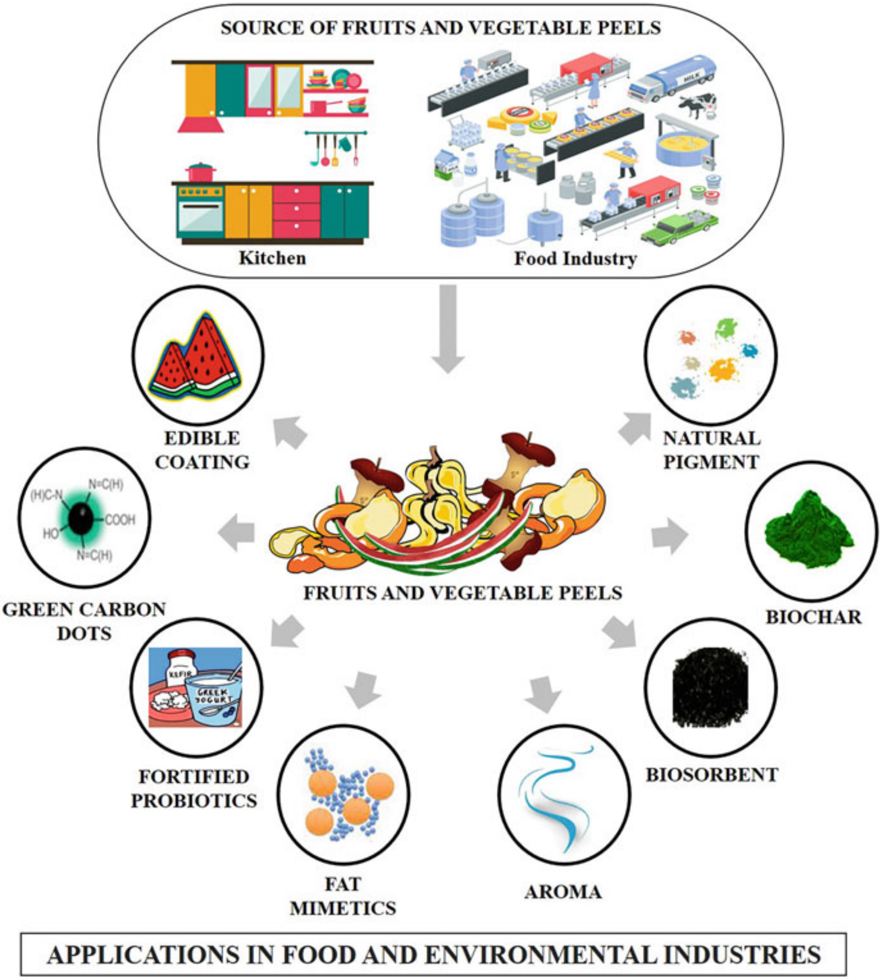


Fig. 11.1 The usage of FVWs in different interventions

vegetables, which remain as overlooked constituents. However, various beneficial products can be obtained from these fruit and vegetable wastes, which are discussed below.

2.1 *Aroma*

Aroma is the chief sensory component that influences significantly the perception of consumers' acceptance of vegetables, fruits, and their products (Crisosto et al. 2006). Aroma in fruit comprises different volatile compounds that vary from species to species, ripeness, cultivar, pre- and postharvest handlings, climatic circumstances, and condition of storage. The volatile components in fruits contain apocarotenoids, ketones, esters, alcohols, lactones, terpenoids, and aldehydes and their glycosidically and free bound forms. Most fruits have higher levels of volatiles or aroma containing aromatic compounds in the exocarp-like peel than in mesocarp and endocarp such as pulp. Peel tissue is characterized with maximum metabolic activity or adequate fatty acid substrates (Hadi et al. 2013). Aromatic compounds are considered as essential components in the food and beverage industry, accounting for approximately 25% of the whole market (Rodríguez-Madrera et al. 2015). Most importantly, consumers choose natural flavored food products for nutrition- and health-conscious lifestyles (Liang et al. 2020). Most fruit peels are considered as a by-product in the food industry because of their flavor compounds and less raw material costs (Table 11.1). Essential oil's aromatic or volatile components are generally classified by the US FDA (Food and Drug Administration 2016) as Generally Recognized as Safe (GRAS) substances and are flavouring in functions that act as natural additives in the maximum food industry (Ribeiro-Santos et al. 2017). Essential oils of citrus peel are widely used for aroma in different food products, including alcoholic, candy, gelatins, and other nonalcoholic beverages (Esmaeili et al. 2012). Also, dried mango peel powder is thought to be a flavoring agent that imparts the characteristic of mango odors (Ruiz et al. 2011) in yoghurt, while apple dried peel powder is used for flavor and aroma in biscuits (Rahman et al. 2020). Volatile oils extracted from mango, orange, and mandarin peel are also used for aroma in healthy instant flavored drinks (Masoud and El-Hadidy 2017).

2.2 Natural Pigments

Generally, colorants or natural pigments utilized in food application are acquired from different renewable resources like plants, insects, and microbes (e.g., algae, bacteria, fungi, and yeasts). Traditionally, the natural pigments are obtained from extracts of turmeric, paprika, saffron, and different flowers (Burrows 2009). Owing to the wide range of applications of pigments, synthetic pigments have gained significant attention to be used as food coloring agents. The advantages of these synthetic compounds are low cost of production, ease of use, high tinctorial strength, and stability. In general, plants are found to contain edible pigments, particularly in colored vegetables and fruits (Table 11.2). This color of fruits and vegetables is usually imparted by secondary metabolites of plants and is commonly stated as natural pigments. Presently, the trends have shifted in which consumers have become highly concerned about their diet, i.e., what they are consuming and their health benefits.

Considering the demand of consumers, it has become essential to explore alternatives of chemical-based pigments (Sigurdson et al. 2017). Therefore, extensive research is being conducted to explore safe and natural food ingredients like natural pigments which exhibit health benefits (Table 11.2). Thus, researchers are now working hard to explore natural food coloring agents that could meet the regulatory

Table 11.1 Main aroma compounds of different fruit peels and their odor description

Fruit	Cultivar/variety/subgroup	Main component	Odor description
Grape	Bastardo	(E)-2-hexenal β-bourbonene, α-caryophyllene, hexanal	Woody, spicy, herbaceous, green
	Aglianico	Free volatiles: (E)-2-hexenal, (E)-2-hexen-1-ol, hexanal Bound volatiles: (E)-2-hexenal Hexanol, hexanal, furaneol, benzyl alcohol, 2-phenylethanol	Free volatiles: Green, herbaceous, grass, fatty Bound volatiles: Green, herbaceous, honey, grass, jam, cotton candy, strawberry caramel, rose, floral, fruity, roasted, fatty toasted, sweet
	Bual	Hexanal, (E)-2-hexenal, β-bourbonene, α-ylangene, α-bisabolene	Woody, herbaceous, spicy, floral, balsamic, green, black pepper
	Uva di Troia	Free volatiles: (E)-2-hexen-1-ol, (E)-2-hexenal bound volatiles: Vanillin, benzyl alcohol	Free volatiles: Herbaceous, green, grass Bound volatiles: Roasted, toasted, sweet, fruity, vanilla, candy
	Muscat	Nerol, geraniol, linalool	Muscat grape floral aroma
	Frontenac	Hexanal, β-damascenone, 2-phenylethanol, (E)-2-hexenal	Floral, herbaceous, honey, sweet, fruity, green, rose
	Maréchal Foch	Hexanal, (E)-2-hexenal	Green, herbaceous
	Marquette	Hexanal, (E)-2-hexenal	Herbaceous, green
	Sabrevois	Hexanal, 2-phenylethanol, (E)-2-hexenal	Herbaceous, green, floral, rose, honey
	St. Croix	β-damascenone, hexanal, 2-phenylethanol, (E)-2-hexenal	Herbaceous, green, sweet, fruity, floral, rose, honey
Mango	Malindi	HDMF, γ-octalactone 2-acetyl-1-pyrroline, (E,Z,Z)-1,3,5, undecatetraene	Cooked rice, caramel, sweet, pineapple, coconut
	White alphonso	HDMF, γ-octalactone, (E,Z)-1,3,5-undecatriene, β-ionone, (Z)-β-ocimene	Caramel, violet, sweet, coconut, pineapple, terpeny
	KhieoSawoei	(E)-2-hexenal, γ-terpinene, hexanal, (E), β-ocimene, (Z)-3-hexen-1-ol	Refreshing citrus-like, herbaceous, grassy, pungent vegetable-like green, gasoline, fruity, green grass-like, cut grass, fatty green, intensely green
	Kensington pride	Bound volatiles: p-mentha-1,5,8-triene, benzyl alcohol, geraniol	Floral, balsamic, sweet, earthy, rose, citronella, fruity, roasted, citrus

(continued)

Table 11.1 (continued)

Fruit	Cultivar/variety/subgroup	Main component	Odor description
	PrayaSowoy	HDMF, (E)-3-hexenal	Caramel, sweet, grassy, green
	Haden	HDMF, ethyl 3-methylbutanoate, ethyl butanoate	Fruity caramel, sweet
	Royal Special	HDMF, γ-octalactone, (E,Z,Z)-1,3,5,8-undecatetraene, β-ionone	Coconut, sweet, pineapple, caramel, violet
Apple	Ponta do Pargo	Hexyl acetate, α-farnesene	Estery, sweet, fruity, wood
	Clara	Benzaldehyde, farnesol, decanoic acid	Fatty, almonds, rancid, floral
	Greensleeves	Hexanal, (E)-2-hexenal	Fatty, fresh, aldehydic, green, grassy, leafy, sweaty, cheesy, fruity
	N/A	β-pinene, α-pinene, α-phellandrene	Citrus, black pepper, terpenic, green, herbal, woody, fresh, sweet, pine, hay, earthy, dry, resinous, camphoreous
	Porto Santo	Hexan-1-ol, α-farnesene	Wood, sweet, herbaceous
	Blanquina	Farnesol, benzaldehyde, ethyl decanoate	Grape, floral, almonds
	Santo da Serra	Hexan-1-ol, α-farnesene	Sweet, herbaceous, wood
	Ernestina	Decanoic acid, benzaldehyde, farnesol	Floral, almonds, fatty, rancid
	Coloradona	Decanoic acid, benzaldehyde, farnesol	Floral, rancid, almonds, fatty
Melon	Queen Anne's pocket melon	Octanol, 2,3-butanediol diacetate, eugenol	Sweet, aldehydic, waxy, woody green, orange, clove, rose, spicy, mushroom
	Oriental sweet melon "Caihong 7"	Hexanal, (E,Z)-2,6-nonadienal, (E, Z)-3,6-nonadienol	Fatty, raw, green, cucumber, bell pepper, fruity, watermelon, fresh
	Oriental sweet melon "Tianbao"	(E)-2-Hexenol, (E,Z)-3, allyl hexyl oxalate, 6-nonadienol, (E,Z)-2,6-nonadienal 2-nonynol, hexanal	Fresh, unripe, leafy, green, fruity, banana, raw, watermelon, cucumber, fatty, grass, bell pepper, aldehydic, sweaty, violet, dry
Citrus fruit	107 citrus germplasms from loose-skin mandarin, papeda, sweet orange, sour orange, lemon, grape and pomelo fruit	d-limonene	Lemon, citrus, orange, fresh, sweet

(continued)

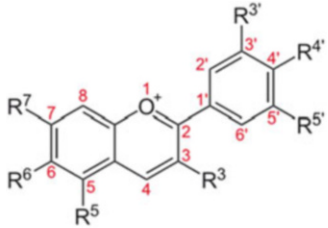
Table 11.1 (continued)

Fruit	Cultivar/variety/subgroup	Main component	Odor description
	Citrus ichangensis "Huaihua"	(Z)-β-farnesene, trans-β-ocimene, β-bisabolene	Citrus, sweet, green, herbal, woody, balsamic
	Orange	Myrcene, limonene	Fresh citrus, peppery, orange, sweet, balsam, terpene, spicy, plastic
	Eureka lemon	Free volatiles:, β-pinene, d-limonene, γ-terpinene Bound volatiles: 8-hydroxylinalool, benzoic acid, vanillin	Free volatiles: Mint, citrus, lemon, wet, resin, woody, pine, turpentine, flower, alcohol Bound volatiles: Flower, alcohol, mint, sweet, lemon
Pitaya fruit	N/A	2-Hexenal, hexanal	Sweet, fruity, almond, green, apple, leafy, plum, aldehydic, vegetable, fresh, fatty, sweaty, grass
Mabolo	N/A	Butyl benzoate, α-farnesene, hexyl butyrate, benzyl butyrate	Amber, fruity, green, balsamic, sweet, apple, waxy, herbal, soapy, appetizing aroma, citrus, myrrh, fresh, lavender, bergamot, neroli, apricot, loganberry, jasmine, and cheese-like
Kiwifruit	Bruno		
		Ripe fruit: Ethyl butanoate, methyl butanoate	Ripe fruit: Juicy fruit, fruity, cognac, pineapple, apple, banana sweet
		Unripe fruit: n-hexanal, (E)-2-hexenal	Unripe fruit: Fresh, fatty, green, aldehydic, leafy, grassy, fruity, sweaty, cheesy, banana
	Sui huang	β-Linalool, benzyl isothiocyanate, benzyl nitrile	Citrus, oily, floral, green, sweet, rose, woody, blueberry, watercress, horseradish, dusty, medicinal

Source: Liang et al. (2020), (License Number: 5115841463988)
HDMF 4-hydroxy-2,5-dimethyl-3(2H)-furanone, *N/A* not available

restriction for biotherapeutics and food application as well as meet the market demands and challenges. As it is well known that natural pigments with both coloring and pharmacological potentials have a broad range of applications in the food industry, other than this it could also be used in the development of new products (like nutraceutical and functional food) because of its health benefits (Fernández-López et al. 2020).

Table 11.2 Natural pigments extracted from vegetable wastes

Type of pigment and raw materials	Method of extraction	Processing condition	Yield	Bioactivity and applications
Anthocyanins				
Apple (*Malus domestica*) peel	Solvent extraction	80% acetone or ethanol	169.7 g cyanidin 3-glucoside equivalents/100 g dried peels	Antioxidants, free radicals scavenger, anti-inflammatory, antiviral, anticancer properties
Banana (*Musa* sp.) peel	Solvent extraction	Methanol, ethanol, acetone, water, acetone/water, methanol/water, or ethanol/water	434 μg cyanidin 3-glucoside equivalents/100 g d.w.	Antioxidant activity, development of drugs and use in functional foods, free radical scavenging properties
Eggplant (*Solanum melongena*) peel	Solvent extraction	70% methanol, 70% ethanol, and 70% acetone	Methanol. 82.83; ethanol, 62.92, acetone, 51.56 mg DGE/100 g DP	Color (pigments) and antioxidant properties
Grape (*Vitis vinifera*) peel	Supercritical fluid extraction (SFE)	45–46 °C, 160–165 kg cm^2 pressure, and 6–7% ethanol	1.176 mg/mL	Radical scavenging activity
Purple potato (*Solanum tuberosum*) peel	Ultrasound-assisted extraction UAE	Ultrasounds for 20 min, 30 °C, with methanol/acetone/water (7:7:6, v/v/v)	6.84 mg/100 g	Antioxidants, anti-inflammatory, anti-mutation, and antitumor properties

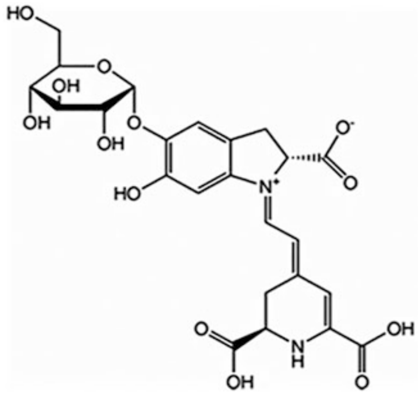
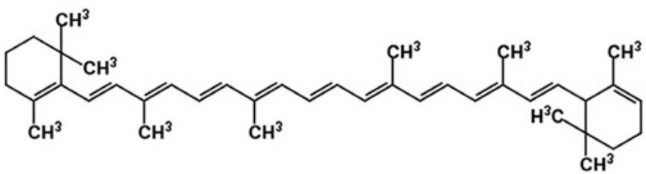
Betalains				
Red pitaya (*Hylocereus polyrhizus*) peel	Solvent extraction	80% acetone	13.8 mg as betanin equivalents per 100 g	Alternatives to synthetic colorants as they possess strong coloring potential, excellent health-contributing properties
Ulluco (*Ullucus tuberosus*) peel	Solvent extraction	Methanol/water (60:40) for 24 h at 10 °C	100 μg/g	Scavenging of free radicals/reactive oxygen species, inhibition of lipid peroxidation and LDL oxidation, prevention of DNA damage, induction of antioxidant, antiproliferative and antimicrobial activities
Carotenoids				

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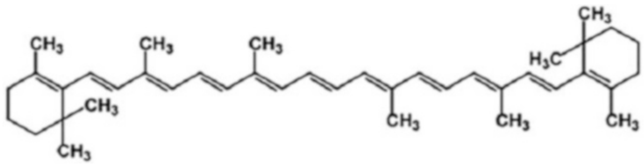
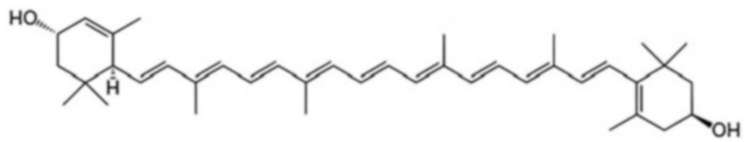
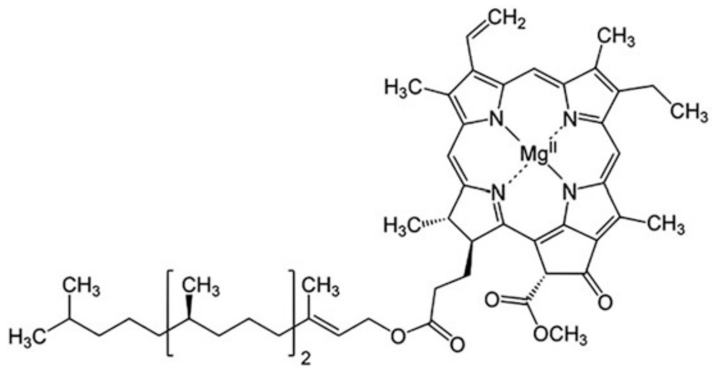
Table 11.2 (continued)

Type of pigment and raw materials	Method of extraction	Processing condition	Yield	Bioactivity and applications
Tomato (*Solanum lycopersicum*) peel	Solvent extraction	Acetone and hexane (50:50)	ND	Antioxidant, antimutagenic, antiproliferative, anti-inflammatory, and anti-atherogenic activities. Carotenoids help to modulate immune response, stimulate intercellular signaling (gap junction) pathways, possess provitamin A activity, regulate cell cycle and apoptosis, and modulate many physiological processes
Gac (*Momordica cochinchinensis*) peel	Solvent extraction	Hexane/acetone/ethanol (50:25:25 v/v/v)	95 to 136 mg/100 g d.w.	Antioxidant activity; β-carotene is a precursor to vitamin A and has been efficiently used to treat the deficiency of vitamin A through the addition of gac aril in the diet
Pomegranate (*Punica granatum*) peel	UAE green solvents	Sunflower and soy oil	0.6134 and 0.6715 mg carotenoids/100 g of dry peels using sunflower oil and soy oil, respectively	Antioxidant, antimutagenic, antihypertension, anti-inflammatory, anti-atherosclerotic, and anti-HIV1 activities; protects against osteoarthritis, prostate cancer, and heart disease
Beta carotene				

Carrot (*Daucus carota*) peel	Solvent extraction	Ethanol +2 N potassium hydroxide	Before drying, 20.45 mg/100 g dry weight; after drying and blanching, 11.11 mg/100 g dry weight	Oral sun protectant for the prevention of sunburn. Anticancer agents, potential treatment of leukemia
Tomato (*Solanum lycopersicum*) peel	Solvent extraction	Sample-to-solvent ratio (1:5 w/v) with methanol, ethanol, diethyl ether, acetone, chloroform, and hexane	6.87 mg/g of extract	Antioxidant activity
Lutein				
Tomato (*Solanum lycopersicum*) peel	Solvent extraction	Sample-to-solvent ratio (1:5 w/v) with methanol, ethanol, diethyl ether, acetone, chloroform, and hexane	1.08 mg/g of extract	Antioxidants, contributes towards maintenance of skin health
Chlorophyll				

(continued)

Table 11.2 (continued)

Type of pigment and raw materials	Method of extraction	Processing condition	Yield	Bioactivity and applications
Cucumber (*Cucumis sativus*) peel	Solvent extraction	Sample-to-solvent ratio (1:5 w/ v) with methanol, ethanol, diethyl ether, acetone, chloroform, and hexane	3.46 mg/g of extract	Antioxidant and antimicrobial activities
Watermelon (*Citrullus lanatus*) peel	Solvent extraction	Sample-to-solvent ratio (1:5 w/v) with methanol, ethanol, diethyl ether, acetone, chloroform, and hexane	5.28 mg/g of extract	Antioxidant potential. Imparts green color to the melon and can be a natural source of pigments to be used in food and pharmaceutical industries

Source: Adapted from Sharma et al. (2021)
NA not defined

Furthermore, the pigments are categorized as synthetic or natural, fat-soluble or water-soluble, and inorganic or organic types. Additionally, they are also categorized on the basis of their natural occurrence, solubility, and structural affinities. In general, the natural pigments are classified into four main groups, i.e., anthocyanins, betalains, carotenoids, and chlorophyll.

2.3 *Edible Coatings/Films*

Edible coating is the thin layer present on the food surface which maintains the characteristic properties, shelf-life, and functionality of food at a low cost (Zaragoza et al. 2018). The edible coating/films are known to be used to extend the shelf-life, prevent spoilage by microbes, and act as carriers for antimicrobial agents (Wu et al. 2012; Prakash et al. 2020). Interestingly, the utilization of these edible coatings is considered to be an operative approach for preservation during the transportation of vegetable and fruits, which easily get affected *via* pre- or postharvesting condition, insects, and microorganisms (Raghav et al. 2016). The utilization of these edible coatings aids in developing a regulated atmosphere to generate mild alteration in fresh and processed food properties like color, firmness, ethylene production, antioxidant properties, sensory quality, organic compounds under anaerobic processes, and microbial growth inhibition (Ullah et al. 2017).

Lately, essential oils (EOs) as well as their other constituents have gained substantial attention as they exhibit effective antimicrobial potential. The EO of lemongrass citral (3,7-dimethyl-2,6-octadienal) has been stated to show antimicrobial potential against diverse food-borne pathogens and is also found to be present in edible coatings (Adukwu et al. 2012). EOs are reported to be safe as they show maximum effect with minor alteration in the organoleptic properties of the food (Alparslan et al. 2017). Latterly, during the development of edible coating, emerging technologies involving diverse nanosystems like nanoemulsions, nanocomposites, and polymeric nanoparticles have been utilized. The nanosystems allow the regulated release of antioxidants and show antibacterial activities on the food surface. Due to the excellent antioxidant potential of different phenolic compounds, vegetables and fruit peels are considered as a suitable entity to be included in coatings and films.

Gelatin obtained from fishes is considered to be a valuable biopolymer that can be used for biofilm fabrication because of their high myofibrillar protein content and biodegradable nature (Etxabide et al. 2017). On the other hand, due to variation in amino acid sequence, vegetable and fruit peel-based films demonstrate low water permeability in comparison to gelatin-based film (mammalian origin). A report unveiled that enrichment of gelatin film with pomegranate peel powder considerably enhanced the water vapor permeability (WVP) because of partial dissolution of pomegranate peel in the matrix of film resulting in the development of more heterogeneous microstructure (Hanani et al. 2019). Both hydrophilic and

Table 11.3 Fruit and vegetable peel-based edible films/coating with their applications

Fruit/vegetable common name	Scientific name	Matrix	Applied on food items	Technique used	Beneficial effects
Apple	*Malus domestica*	Carboxy methylcellulose	Fresh beef patties	Microfluidization	A complete inhibition of lipid oxidation and efficient suppression of the growth of microbes on raw beef patties. No effect on the sensory characteristics of raw and cooked beef patties
Orange	*Citrus sinensis*	Gelatin	Cupcake	ND	Increase in peroxide value by 3.60–4.80 (mL.eq./kg fat) in refrigerated storage for 1 week and decrease in microbial growth
Pomegranate	*Punica granatum*	Mung bean protein	NS	ND	The films enriched with pomegranate peel also showed higher total phenolic content, antioxidant activity, and antibacterial capacity compared to the control mung bean protein film. These films found their use in food industry to develop bio-functional edible films intended for packaging of food products
Potato	*Solanum tuberosum*	Oregano essential oil (OEO)	Cold-smoked salmon	ND	When samples were coated with potato processing waste-based-oregano oil-incorporating film (PPW-OO), the *Listeria* population decreased from 6.7 to 4.7 log CFU/g by the end of storage. Incorporation of oil into the films reduced the film strength and increased their water vapor permeability. The PPW-OO film reduced the growth of *Listeria monocytogenes* on cold-smoked salmon during storage under vacuum conditions at 4 °C for 28 days
Orange	*Citrus sinensis* (L.) Osbeck	Chitosan film	Deepwater pink shrimp	Casting	The combination of chitosan film with 2% orange peel essential oil concentration was effective in prolonging the shelf-life of fresh shrimps to 15 days
Orange	*Citrus sinensis* (L.) Osbeck	Gelatin	Shrimps	ND	Gelatin coating combined with orange peel essential oil preserved shrimp quality during cold storage with a shelf-life extension of about 6 days

Lemon	*Citrus limon*	Cassava starch and sodium alginate	Tofu, strawberry	ND	The addition of 0.6% lemon peel essential oil (LPEO) to tofu and 1% LPEO to strawberry with each of edible coating agents was significantly able to reduce their degradation
Orange	*Citrus sinensis*	Carnauba wax, montmorillonite nanoclay	Blood orange	ND	Blood orange coated by carnauba wax with montmorillonite nanoclay (MMT) had the least deformation and dissolved solid and the highest acidity compared to other treatments. Fruits coating with MMT showed better brightness
Orange	*Citrus sinensis*	Pectin-coating	Fresh-cut orange	ND	The results showed that the nanoemulsion-based edible coatings containing orange peel essential oil can extend the shelf-life of orange slices without any undesirable impacts on sensory attributes

Source: Adopted from Kumar et al. (2020a)
NS not specified, *ND* not defined

hydrophobic constituents of pomegranate peel equalize the hygroscopic properties and do not affect the film's moisture content (Table 11.3).

Another study using the potato peel revealed the presence of adequate number of fermentable sugars, hemicellulose, cellulose, and starch (Borah et al. 2017). On investigation, the film containing low concentration of potato peel when compared with film containing high concentration of potato peel showed higher WVP because of the presence of large pore size of matrix of film despite its dense structure (Borah et al. 2017). Hence, film coating of potato peel biopolymer has been found useful for fabricating biodegradable food packaging for commercial usage. Even though, polyethylene/fish gelatin bilayer films solubility has been reported to be lowered via enriching them with various fruit peels (Hanani et al. 2018).

2.4 Substitutes and Mimetics of Fat

The form and consistency of fat is vital for texture, taste, and sensory qualities in meat items since fats are essential elements in the product's color, tenderness, taste, juiciness, hardness, and shelf-life (Weiss et al. 2010). The major drawback of presenting low-fat products is overall unpleasant appearance (products are typically darker), including taste and color. Moreover, they contain less flavor and accelerate the reduction of lipophilic aromatic compounds such as phenylpropanoids and terpenes (Tomaschunas et al. 2013). In terms of color changes, the substitution of fat used in cooked products raises non-enzymatic darkening reactions caused by interactions between the meat amino acids and fat carbohydrate substitutes (Colmenero 1996). In terms of rheology, fat reduction causes meat emulsion destabilization because fat works as a spacer between three-dimensional networks of proteins; sometimes adding a little amount of fat results in destabilization (Álvarez and Barbut 2013). Therefore, ingredients with low calorie have been found to preserve the product's qualities as per need (Brewer 2012). Polymers of carbohydrate including starches, insoluble fibers and pectin most reported yet and have ability to hold water, shape gels and their three-dimensional networks, stabilize emulsions, and retain adhesiveness and viscosity (Figuerola et al. 2005; Elleuch et al. 2011). It is worth refering that fat content replaced by some ingredients works as fat substitutes. They have fatlike structures, primarily fatty acids, and are usually substituted in the same proportion as the real product. Also their functionalities are similar to fats, mostly physical and sensory, but are not replaced in equal ratios (fat mimetics are commonly used in fat products) (Peng and Yao 2017). Tomato pomace, for example, has 25.4–50% fiber (usually dry basis), with 15.4–23.7% proteins, 5.4–20.5% lipids, and 4.4–6.8% minerals in the majority of agro-industrial residues (Del Valle et al. 2006). Fruits can't be discarded due to their maturity as they contain fiber that are essential ingredients usable in low-fat product formulation (Table 11.4). For instance, green bananas have 6% to 15.5% dietary fiber and 40.9% to 58.5% resistant starch, respectively. The resistant starch is the key ingredient of functional goods for people suffering from diabetes as well as metabolic syndromes (Tribess

Table 11.4 By-products as substitutes and mimetics of fat

By-product	Extraction method	Meat product	Fat reduction %	% by-product in meat product	Changes in product
Tomato peel powder	Dehydrated and crushing by conventional method to 0.5 mm	Beef and pork sausages	15%	0.5%	Rise in free water; structure denser and become more compact; overall sensory acceptability
	Dehydrated and crushing by air-flow ultra-micro-crushing to 0.025 mm	Beef and pork sausages	15%	0.5%	Increased free water and increased color
Tomato fiber pectin (*Lycopersicon esculentum*)	Acidified ethanol	Beef burger	12.5, 25, 37.5, and 50%	2.5, 5, 7.5, and 10%	Lowered lightness on basis of concentration, lowered energy and pH values, and lessened cooking loss %
Apple pomace fiber (*Malus domestica* cv. Tsugaru) sausages	Dehydrated (55 °C) and starch remotion (gelatinized, 95 °C), washed with hot water (100 °C) and ethanol (preheated to 60 °C) and dried at 55 °C	Uncured, reduced fat chicken	17–33%	2%	Lessened loss of cooking, increased stability of emulsion and color value, and lessened pH value; improved texture profile of sausages compared with fat reduction control
Pineapple peel and pomace	Mill and inactivation of bromelain (100 °C, 2 h)	Beef burger	50%	1.5%	Decreased acceptance in the sensory analysis; in raw burgers, reduced the pH value, redness, and lightness; in cooked burgers, reduced redness, reduced cooking loss, and increased the hardness

Source: Calderón-Oliver and López-Hernández (2020), (License Number: 5115850378470) et al. 2009; Fuentes-Zaragoza et al. 2010). Furthermore, in hamburger meat bananas, pulp, and peel are reported as substitutes of fat as compared to oatmeal and apple peel that are currently being used (Bastos et al. 2014).

2.5 Fortified Probiotics

Fruits have been used in medicine for over two centuries to treat sore throat, extreme thirst, and cough. In recent years, there has been a rise in probiotics and functional foods in the market. Probiotic foods are widely consumed worldwide and are regarded as essential functional food items (Abdel-Hamid et al. 2020). Fruits and peels are also rich in bioactive compounds and have a high value. These active ingredients are found in abundance in pomegranate (*Punica granatum*) peel, citrus peel, barbary fig (*Opuntia ficus-indica*) peel, and mango peel containing oligosaccharides (as prebiotics), antioxidants, and fiber (Cerezal and Duarte 2005; Crizel et al. 2013; Chan et al. 2018; Coelho et al. 2019). Both dietary fiber and probiotics were studied, and it was found that they can lower incidence of constipation and colon cancer (Drago 2019). Furthermore, fruit-derived dietetic fibers showed significant impact on the bacteria viability and are suggested as a viable ingredient in probiotic dairy foods (do Espírito Santo et al. 2012). Several practices have been done to improve probiotics' biological activities by including fruit peel supplementation.

Probiotic yoghurt formed by using peel powder of pineapple (*Ananas comosus*) exhibited anticancer, antibacterial, and antioxidant activities and showed improved antibacterial activity against bacteria *Escherichia coli*. However, no significant impact has been recorded against *Staphylococcus aureus* (Sah et al. 2016). Supplementing peel powder of apple (*Malus domestica*), passion fruit (*Passiflora edulis*), and banana (*Musa*) to probiotic yoghurt enhanced rheological properties as well as increased the growth of *Lacticaseibacillus paracasei*, *Lacticaseibacillus casei*, *Lactobacillus acidophilus*, and *Bifidobacterium animalis* subsp. *lactis* (do Espírito Santo et al. 2012). In fermented products, the impact of mango peel supplementation was also determined on antioxidant properties and microbe growth rates in kefir (Vicenssuto and de Castro 2020). To produce fat- and sugar-free probiotic set yoghurt, composite peel powder of fruits (pineapple, passion fruit, and orange) was used in different amounts as 0.7, 0.5, and 1.0% (w/v), respectively (Dias et al. 2020). Yogurt infused with 0.5% peel mixtures showed increased firmness, market acceptability, decreased high lactic acid bacteria counts, and syneresis.

3 Environmental

The fruit and vegetable wastes have started to impose environmental issues owing to improper disposal either in landfills or water bodies like river streams. These practices have led to serious environmental issues as they easily get degraded because of high moisture content, which often results in microbial spoilage. But their application in synthesizing green carbon dots, biochar, and biosorbents has paved the way for new avenues for exploration, which are discussed below.

3.1 Green Carbon Dots

Carbon dots (CDs) are photoluminescent, tiny (less than 10 nm) materials that can be produced in two ways: top-down and bottom-up (Fan et al. 2020; Kumar et al. 2020b). A broad carbon structure is broken down from top-down synthetic route by using laser ablation, electro-oxidation, and acid-assisted chemical oxidation in the synthesis (Wang and Hu 2014). However, this method necessitates a severe synthetic and complex condition and is believed to be the drawback of this method. The other approach like bottom-up relies on plants and their by-products rather than chemicals and was found to be superior to the top-down approach. Food wastes have economic advantages and are believed to be the most promising raw materials as a carbon source for CD synthesis (Fan et al. 2020). Mango and pineapple peels are stated to be ideal for CD production because they contain functional elements such as polyphenols, gallic acid, dietary fiber, flavonoids, carotenoids, and mangiferin (Ajila et al. 2007; Rattanapoltee and Kaewkannetra, 2014). Vegetable and fruit by-products are sources of nutritious dietary fiber, antioxidants, and antibacterial agents evident from the growing number of publications (Pérez-Jiménez and Saura-Calixto 2018). Moreover, these vegetable and fruit by-products are also ideal starting materials for CDs due to their low toxicity, low cost, photostability, innocuousness, and biocompatibility properties (LI. Cao et al. 2013; Iravani and Varma 2020). To synthesize CDs, the following processes are involved during peel treatment, such as pyrolysis at high temperatures and oxygenolysis with nucleation, carbonization, polymerization, concentrated acid, and oxidation (Jiao et al. 2019). CDs have shown promise in biomedical applications such as energy storage devices, pathogen detection, environmental studies, heavy metal and additive detection in food, and water purification processes (Table 11.5) (Tyagi et al. 2016; Huang et al. 2019).

3.2 Biochar

Biochar is a stable carbon-enriched solid produced by pyrolysis, which occurs when organic feedstock material is thermochemically decomposed at high temperatures in an oxygen-free environment (Bruno et al. 2009). Biochar has been generated using various types of food waste, and its yield and physicochemical properties have been published (Oh et al. 2017; Carmona-Cabello et al. 2018). Biochar is often used to extract various forms of heavy metal-containing pollutants from polluted water sources (Liu and Zhang 2009; Inyang et al. 2012; Xu et al. 2013). It also acts as a catalyst for the production of bioethanol generated by biological waste obtained

Table 11.5 Vegetable and fruit peels as a source of carbon in carbon dot preparation

Scientific name	Fruits/ vegetable common name	Detection limit of heavy metals	Production conditions	Applications
Allium cepa	Onion	NA	Microwave-assisted/ 1000 W/a specific time intervals	Skin wound healing; living cell imaging
Mangifera indica	Mango	1.2uM	Hydrothermal/300 °C/ 2 h	Cellular labeling Fe^{2+} detection
Citrus limon (L.)	Lemon	73 nM	Hydrothermal/200 °C/ 8 h	Cr^{6+} sensing; photocatalysis effect
Ananas comosus	Pineapple	4.5 nM	Hydrothermal/200 °C/ 3 h	Electronic security devices Hg^{2+} quantification
Musa acuminata	Banana	NA	Microwave-assisted/ 500 W/20 min	Determination of colitoxin DNA
Citrus limetta	Sweet lemon	NA	Hydrothermal/180 °C/ 3 h	Breast cancer detection gene therapy
Citrus sinensis	Orange	NA	Hydrothermal/150 °C/ 10 h	Photocatalytic activity
Citrus maxima	Pomelo	0.23 nM	Hydrothermal/200 °C/ 3 h	Hg^{2+} sensing
Citrullus lanatus	Watermelon	NA	Hydrothermal/220 °C/ 2 h	Imaging probe
Citrus paradisi	Grapefruit	NA	Hydrothermal/190 °C/ 12 h	Photoluminescence immunoassay
Citrus sinensis, *citrus Limon*	Citrus	0.01 μM	Hydrothermal/180 °C/ 2 h	Fe^{3+} and tartrazine sensing; cell imaging
Punica granatum	Pomegranate	NA	Hydrothermal/180 °C/ 36 h	Recovery of latent prints
Garcinia mangostana	Mangosteen	NA	Hydrothermal/200 °C/ 30 min	Cell imaging
Musa acuminata	Banana	211 nM	Hydrothermal/200 °C/ 2 h	Selective and sensitive detection of Fe^{3+} ions

Source: Kumar et al. (2020a)
NA not applicable

from food processing plants and various agricultural crop matter remains such as bran, husk, and other grains (Cao et al. 2009; Yao et al. 2011). Biochar can be made from a variety of fruits and vegetable peel wastes which have been comprehended in Table 11.6.

Rapid pyrolysis with the fluidized bed method was used to produce biochar from potato (*Solanum tuberosum*) peel waste to remove H_2S (Sun et al. 2017). In biochar made from pineapple (*Ananas comosus*) peel, H-bonding interaction with oxytetracycline is responsible for its sorption. Parameters of thermodynamics, on the other

Table 11.6 Vegetable and fruit peel-derived biochar and its applications

Scientific name	Fruit/ vegetable common name	Process conditions required for biochar formation	Applications
Musa; *Citrus sinensis*	Banana; orange	Pyrolysis at 500 °C for 10 min	Displayed fine quality performance in lowering the biochemical oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD) concentration, and grease and oil of palm oil mill effluent (POME) to an acceptable level below the discharge
Ananas comosus	Pineapple	Pyrolysis at 750 °C for 2 h	Hexavalent chromium/Cr (VI) sorption capacity was 7.44 mg/g
Musa	Banana	Hydrothermal carbonization at 230 °C for 2 h	Exhibited fine capability in lead clarification of 359 mg/g and 193 mg/g, respectively
Solanum tuberosum	Potato	Pyrolysis at 500 °C for 5 min	Hydrogen sulfide (H_2S) was achieved 53 mg/g at 500 °C, under space velocity (8000 L/min/kg)
Citrus maxima	Pomelo	Pyrolysis at 450 °C for 1 hr	Biochar of one gram adsorbs 150 mg/L methyl orange dye
Litchi chinensis	Litchi	Hydrothermal carbonization at 180 °C for 12 h	Adsorption capacity for malachite green and Congo red was 2468 and 404.4 mg/g
Ananas comosus	Pineapple	Pyrolysis at 200 °C for 2 h and then heated at 650 °C for 3 h	Sorption of oxytetracycline
Ananas comosus; *Citrus sinensis*; *Hylocereus undatus*	Pineapple; orange; dragon fruit	Pyrolysis at 300 °C for 2 h	Maximum adsorption capacities of NH^{4+} were related with pineapple peel (5.60 mg/g) and orange peel biochars (4.71 mg/g) produced at 300 °C for 2 h. the NH^{4+} maximum adsorption capacity of the dragon fruit (pitaya) peel biochar formed at 400 °C for 2 h was 2.65 mg/g
Citrus maxima	Pomelo	Pyrolysis at 450 °C for 1 h	A 0.05 g of biochar adsorbed 57.637 mg/g of Cr (VI)
Citrus limetta	Sweet lime	Pyrolysis at 450 °C for 1 h	Removal efficiency maximum was found to be 95% with 120 mg/L of initial Cr(VI) concentration with 3 g/L of biochar dose
	Rambutan		

(continued)

Table 11.6 (continued)

Scientific name	Fruit/ vegetable common name	Process conditions required for biochar formation	Applications
Nephelium lappaceum		Pyrolysis at 600 °C for 3 h	Adsorption for copper ion/cu (II) removal from water solutions of 50 and 100 mg/L at 0.2 and 0.4 g/L adsorbent dosages, respectively
Punica granatum	Pomegranate	Pyrolysis at 300 °C for 2 h	Cu(II) adsorption was 52 mg/g

Source: Kumar et al. (2020a)

hand, revealed that oxytetracycline sorption onto biochar is a spontaneous and endothermic method (Fu et al. 2016). Biochar made from the peels of *Ananas comosus* (pineapple), *Citrus limetta* (sweet lime), and *Citrus maxima* (pomelo) has been reported to extract hexavalent chromium from aqueous solution (Wang et al. 2016; Wu et al. 2017). In another study, copper (II) ions were removed from aqueous and soil systems using biochar made from *Nephelium lappaceum* (rambutan peel) and *Punica granatum* (pomegranate peel) (Selvanathan et al. 2017; Cao et al. 2019). Malachite green, methyl orange, and Congo red were removed from wastewater using biochar made from *Citrus maxima* (pomelo) and *Litchi chinensis* (litchi) peels (Zhang et al. 2019; Wu et al. 2020).

3.3 Biosorbents

Biosorption is a process in which a sorbate (i.e., an atom, ion, or compound) reacts with biomass or biomaterial (referred to as biosorbent), causing sorbate ions to acclimate to the surface of biosorbents, lowering the sorbate concentration in the solution (Niazi et al. 2016). This mechanism has received a lot of attention because of its ability to immobilize heavy metals present in contaminated water (especially from mining and electroplating industries) or metal-forming industries. Various biomasses such as algae, yeasts, fungi (e.g., *Mucor rouxii*), as well as bacteria (*Bacillus thuringiensis*) (Vijayaraghavan and Yun 2008; J. Wang and Chen 2009) have been used to produce a variety of biosorbents. The contribution of different processes that explain how biosorbents function in removing various pollutants is represented in the natural biomass complex compendium; however, these methods still continue to be explored. Many functional groups including carboxyl, amine, hydroxyl, amides, carbonyl, phenolic, sulfhydryl, phosphate, and sulfonate groups are joined with such biosorbents to attract and sequester contaminants, depending on the type of biosorbents and their functional groups (carboxyl, amine, hydroxyl, amides, carbonyl, sulfonate, sulfhydryl, phosphate, and phenolic groups) attached to it (Park et al. 2010; Abdi and Kazemi 2015).

Table 11.7 Vegetable and fruit peel-derived biosorbents and their applications

Scientific name	Fruit/ vegetable common name	Drying temperature/ time	Applications
Malus domestica	Apple	60 °C/24 h	Adsorbed 107.52 mg/g of methylene blue
Allium sativum	Garlic	60 °C/24 h	Adsorbed 142.86 mg/g of methylene blue
Ananas comosus	Pineapple	70 °C/48 h	Adsorbed 97.09 mg/g of methylene blue
Musa paradisiaca	Banana	60 °C/5 h	Removed 90% lead (II) and cadmium (II) ions
Hylocereus undatus	Dragon fruit	105 °C/24 h	A dosage of 0.06 g adsorbed 192.31 mg/ g of methylene blue
Lansium domesticum	Langast	60 °C/24 h	Adsorbed 10.1 mg/g of nickel
Cucumis sativus	Cucumber	95 °C/24 h	A dosage of 4 g/L adsorbed 81.4% methylene blue
Citrus paradisi	Grapefruit	105 °C/24 h	Adsorbed 52.48 mg/g copper ion/ Cu(II)
Citrus reticulata	Ponkan fruits/Mandarin orange	RT/days	Adsorbed 112.1 mg/g of lead (II) ions
Musa	Banana	RT/4 days	A dosage of 0.3 g adsorbed 81.07% of rhodamine B
Musa	Banana	80 °C/48 h	Adsorbed 97 mg/g color, 25 mg/g TSS, and 90.5 mg/g COD removed from palm oil mill effluent (natural banana peel); adsorbed 137.5 mg/g, 28.5 mg/g, and 93 mg/g for color, TSS, and COD removed (methylated banana peel), respectively
Citrus reticulata	Ponkan fruits/Mandarin orange	60 °C/24 h	Adsorbed 1.92, 1.37, and 1.31 mmol/g of nickel (II), cobalt (II) and copper (II) ions, respectively
Solanum tuberosum/ *Daucus carota* subsp. *sativus*	Potato; carrot	60 °C/48 h	A dosage of 3.0 g adsorbed 79.32% of nickel
Luffa acutangula	Sponge gourd	60 °C/24 h	A dosage of 8 g/L adsorbed 69.64 mg/g of malachite green
Lagenaria siceraria	Bottle gourd	80 °C/24 h	Adsorbed 99% copper, 95% silver and iron

RT room temperature

Many studies have been conducted to produce biosorbents from fruit peels, such as *Malus domestica* (apple), *Ananas comosus* (pineapple), and *Hylocereus undatus* (dragon fruit), and vegetable peels, such as *Cucumis sativus* (cucumber) and *Allium sativum* (garlic), to eliminate methylene blue dye from ionic solutions (Table 11.7)

(Hameed and Ahmad 2009; Krishni et al. 2014; Enniya and Jourani 2017; Shakoor and Nasar 2017; Jawad et al. 2018). In batch mode, *Luffa acutangula* peel (sponge gourd) was considered a low-cost natural biosorbent for removing malachite green, a cationic dye (Singh et al. 2018). To eliminate rhodamine B, a cationic water-soluble dye, the banana peel (*Musa*) was reported a very effective biosorbent (Mohammed and Chong 2014). Another research revealed that banana peel-activated carbon, methylated banana peel, and natural banana peel are considered as good biosorbents that were used to treat palm oil mill effluent (Lam et al. 2016).

4 Conclusion

In the present scenario, exploration of sustainable solutions to manage FVWs has become utmost important. Thus, there is dire need for expedition of a solution where the waste material can be used to its full potential and aid in providing the environmental, economical, and social benefits. Moreover, the use of peels of fruits and vegetables in developing valuable products like fortified probiotics, fat mimetics, volatile compounds, carbon dots, biosorbents, and biochar will emerge as an environment friendly and sustainable approach to generate new business opportunities. Other than this, it will unveil the new possibilities for functional use of the waste in various academic and industrial research. Currently, most interventions that are using the FVW are in their initial stages, and there is still demand for more exploration in this direction. Therefore, there is a need for the formation of consortium between industries and academic research to work in alliance so that these wastes could be effectively used. Furthermore, more promotions are needed to be done for utilizing the fruit and vegetable waste for synthesizing valuable commodities.

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Chapter 12
Biomolecules from Orange and Grape Waste: Direct and Indirect Obtaining

Dafne Angela Camargo, Milene Stefani Pereira, and Luciana Francisco Fleuri

Abstract Orange and grape crops play a significant role in the Brazilian economy. Industrial processing generates large amounts of fruit wastes, which emerge as sources of enzymes and other bioactive compounds of interest in several studies due to their different biotechnological applications. The method adopted to obtain biomolecules plays an essential role in reducing costs with bioprocessing; thus, both isolated (direct use) and fermented (indirect use) waste types are seen as sustainable alternatives to chemical technologies. High commercial value enzymes such as phytases, lipases, and proteases are widely used in catalytic processes since they have versatile biochemical properties and broad applications. Their antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and cell modulation actions enhanced the biological potential of orange and grape waste. Therefore, this chapter emphasizes enzyme obtainment and the biomolecules mentioned above from orange and grape waste.

Keywords *Citrus sinensis* L. Osbeck · *Vitis vinifera* · *V. labrusca* · Phytases · Lipases · Proteases · Antioxidant · Antimicrobial · Antidiabetic · Anti-inflammatory · Cellular modulation activity

1 Introduction

Based on a report released by the United Nations (2019), the world population will reach 9.7 billion people over the next 50 years, and it will increase the global demand for food. However, approximately 1.3 billion tons of wastes are generated every year. This amount corresponds to 33% of the total food produced in the world (FAO 2019a).

Brazil is included in the group of countries in Latin America and the Caribbean that, all together, account for 20% of the global food waste – all these wastes are

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generated from harvesting losses to final product retail (FAO 2019b). The losses in this group can reach US$ 29 billion (FAO 2021) and, globally, US$ 936 billion per year in social costs and US$ 1055 billion in economic costs (FAO 2015).

The Brazilian economy is strongly dependent on agricultural production. The volume of processed plant products associated with inadequate storage, distribution, and harvest accounts for partial losses of these products, as observed in the processing of corn, soybeans, wheat, sugarcane, rice, coffee, cassava, and fruits, among others (Parfitt et al. 2010).

In addition, different waste types have little or no commercial value and/or noble destinations. Thus, industries should treat waste in a proper way (Martínez et al. 2012). Processing industry waste is frequently incinerated, used as feed and fertilizer increment, or discarded in landfills (Wu et al. 2014; Tamayo et al. 2011).

Countless waste varieties can be used as a source of high commercial value products, such as sugarcane bagasse; wheat, soy, and cassava bran; coffee husk; corncob; and core and fruit peel (Tlais et al. 2020; Castro and Sato 2013; Hashemi et al. 2010). However, this chapter aims to describe the potential of citrus and viticulture waste, which is quite expressive in Brazil.

2 Orange and Grape Waste

Orange and grapes are two important fruit crops cultivated worldwide. However, during the processing of juice from these fruits, a huge amount of wastes are generated.

2.1 Citriculture Waste

The world produced 49.4 million tons of orange fruits (*Citrus sinensis* L. Osbeck) in the 2019/2020 harvest. According to estimates, this volume is expected to increase by 3.6 million tons in the current harvest (USDA 2021). CITRUSBR (2020a) reported an increase of 26.6% in the total export of frozen and concentrated and pasteurized juice in the first 6 months of harvest in the early 2020s.

Brazil ranks first in the world orange juice production and export ranking. The country was followed by the United States, with 4.9 million tons, and China, with 7.3 million tons. In total, 17 million tons of oranges were produced in the 2019 harvest in Brazil, and total exports of orange juice added US$ 1.7 billion, a 14% increase in the 2019/2020 harvest (CITRUSBR, 2020c). The Brazilian orange production is well-established and acknowledged; however, 43% of the fruits become waste at the juice production processes. Thus, in the last year alone, more than eight million tons of waste were generated (Okino-Delgado et al. 2017, 2019; Cypriano et al. 2017; Lanza 2003).

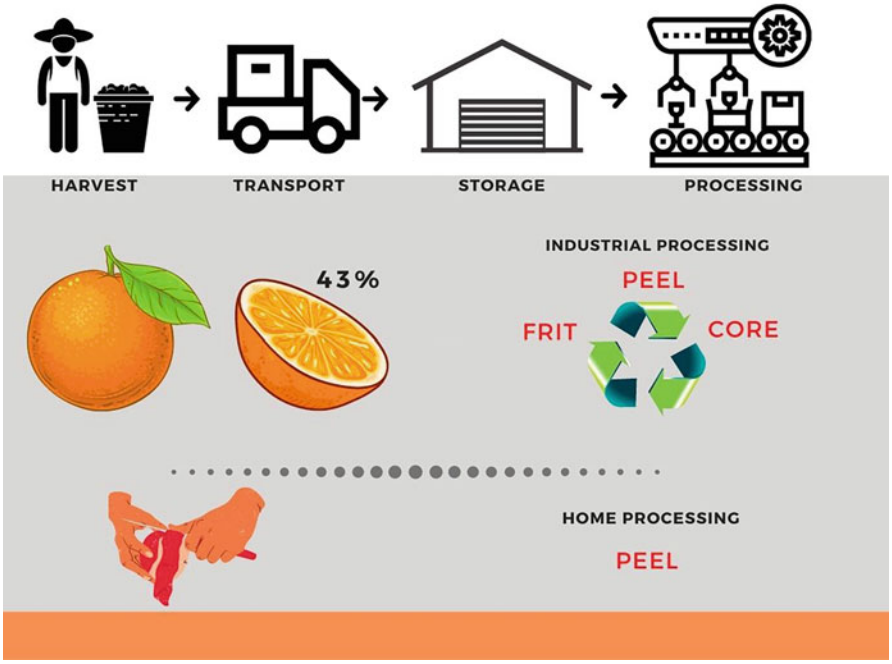

Fig. 12.1 Industrial chain of orange processing for juice production purposes, waste obtained based on industrial (bagasse or core, peel, and frit) and home (peel) processing methods

The most consumed orange varieties in Brazil are Bahia, Pêra, Natal, Valencia, Hamlin, Westin, and Rubi (CITRUSBR 2020b); they are processed in industrial extractors used for citrus juice production. Most studies investigate manually obtained waste, making it hard to standardize the obtainment process and reproduce it at a large scale. Nevertheless, it is worth drawing attention to the industrial processing depicted in Fig. 12.1, which has already been acknowledged as a potential tool to obtain lipases from waste derived from different orange varieties (Okino-Delgado et al. 2019; Okino-Delgado and Fleuri 2014). Nowadays, this sector is entirely mechanical and does not change the biochemical properties of biomolecules. This process generates three fraction types, i.e., bagasse or core, peel, and frit (JBT Foodtech 2020; Okino-Delgado and Fleuri 2014). These waste types consist of lignocellulosic materials rich in compounds such as pectins, essential oils, lignin, vitamins, and soluble sugars (Okino-Delgado et al. 2018; Rezzadori et al. 2012; Aranha and Jorge 2013).

2.2 Vitiviniculture Waste

Wine production represents one of the largest agricultural activities in the world. It recorded 29.2 billion liters in 2018, which represents 17% recovery compared to the previous year. According to the OIV (International Organization of Vine and Wine), in 2018, global grape cultivation reached 78 million tons (OIV 2019). Approximately 80% of this harvest was destined for wine production, and it generated peel, stem, and seed waste; this total represents 20% of the processed weight of the fruit (Teixeira et al. 2014). These waste types are excellent resources, although their commercial and biotechnological potential remains underexplored.

Grape production in Brazil accounts for 1.5 million tons of grapes a year; 50% of this total accounts for table grapes, 24.5% for wine production, 24.5% for juice production, and 2% for making industrialized products (Embrapa 2018). Grape exports in 2018 reached US$ 8.42 million, and it corresponded to a 182% income increase from 2005 to 2018. In 2019, Brazil exported 3.7 million liters of wine and sparkling wine and approximately 39.8 thousand tons of fresh grapes. This volume led to a profit of US$ 88 million, which corresponded to 88% of grape production chain exports (CONAB 2019).

Vitis vinifera is the main grape species destined for wine production, and Cabernet Sauvignon is one of the cultivars with the most significant demand for implantation in the country (Bowers and Meredith 1997). However, this cultivar presents late maturity levels; therefore, the variety Cabernet Franc – early maturation, approximately 20 days – is an alternative replacement in vineyards since it does not fully ripen, mainly in cold years or in years accounting for high rainfall volume (Brighenti et al. 2013). In addition, the variety Cabernet Franc produces softer wine with higher tannin content, controlled acidity, and strong presence of herbal aromas scent of fresh and citrus notes (Wines of Chile 2019). Unfortunately, few studies have addressed this variety in any sphere, which opens room for further research.

The wine production generates bark and seed bagasse with rich functional composition and high nutritional value (Rubilar et al. 2007; Ghafoor et al. 2010; Zhu et al. 2012). The magnitude of agro-industrial waste generation has been minimized by developing new technologies focused on reusing biomass in bioprocesses to obtain bioactive substances with high added and biochemical values such as enzymes, pigments, biofuels, and antibiotics, among others. This recovery helps reduce environmental impacts and production costs (Cunha et al. 2016).

3 Direct and Indirect Obtainment of Biomolecules Deriving from Waste

Different waste types can be used as direct sources of biomolecules or substrates for fermentation processes, which feature the indirect obtainment of biomolecules (Athanázio-Heliodoro et al. 2018; Okino-Delgado et al. 2018). Okino-Delgado

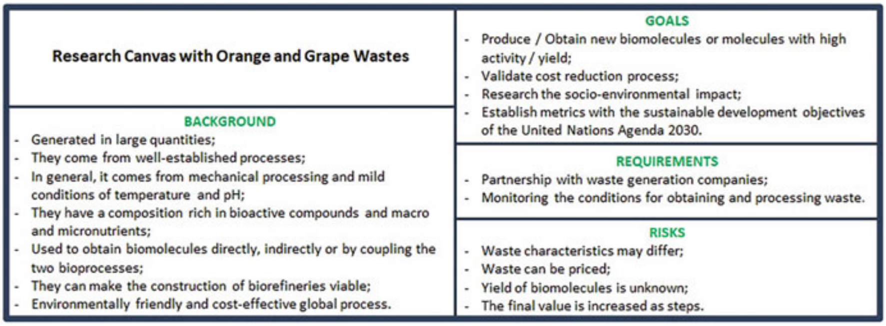

Fig. 12.2 Canvas-based bioprocess analysis. Overview of the advantages and precautions are taken in orange and grape waste reusing

et al. (2018) and Bharathiraja et al. (2020) reviewed studies about orange and winery waste to produce enzymes, organic acids, biofuels, and biosurfactants and have emphasized the relevance of biorefineries from these fruits. The obtainment of different biotechnological products and high benefits from waste types generated in fruit processing would allow integrating and optimizing processes that could be considered more sustainable and cost-effective.

It is important to conduct more research to improve the use of fruit waste as raw material for new products (Fig. 12.2). This Research Canvas exposes attention to opportunities and risks to enable the study to be likely more assertive. Research is the primary waste valuation tool since it outlines different ways to expand waste use and applications.

Based on these waste types and bioprocesses, it is possible obtaining enzymes and molecules presenting biological activity, whose details are described in the following topics.

3.1 Enzymes

The demand for clean technologies has mobilized large companies to invest in enzymatic processes to replace chemical catalysts (Choi et al. 2015). In 2018, the production of biocatalysts accounted for US$ 5.5 billion in the world market, and the growth rate was based on 4.9% a year, which means an increase of US$ 7 billion until 2023 (BCC Research 2018). However, the Brazilian biocatalyst policy is mostly based on enzyme imports (Soccol et al. 2017); hence, it is important to consider orange and grape waste as a biomolecule source (Fig. 12.3). This figure briefly presents the potential of orange and grape waste to be used as a matrix to obtain direct and indirect (substrate for solid-state fermentation) added value molecules.

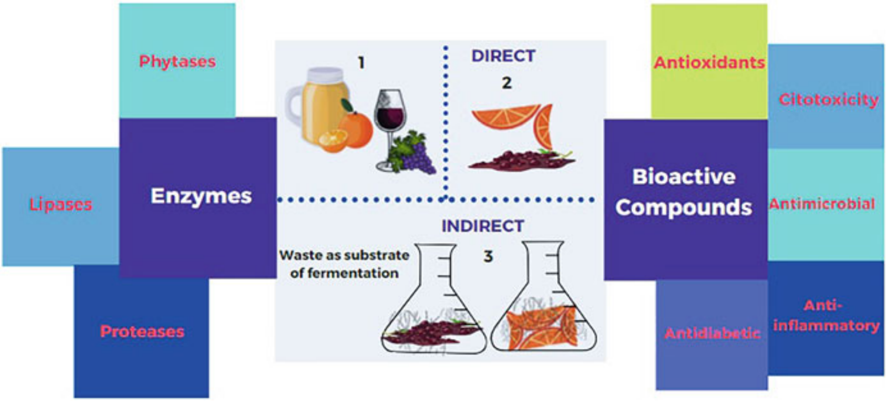

Fig. 12.3 Direct and indirect obtainment of biomolecules from orange and grape waste

3.1.1 Lipases

Lipases (EC 3.1.1.3, triacylglycerol *lipase*) hydrolyze triacylglycerol or synthesize fatty acid esters (Miranda et al. 2015) found in the oil-water interface. These biocatalysts can reverse chemical reactions under water shortage conditions due to reactions such as esterification and transesterification (Vescovi et al. 2016). According to Andualema and Gessesse (2012), lipases have different specificity, stability, and regioselectivity properties (Barbosa et al. 2015). Therefore, they have great potential for the overexploited lipid market, which accounts for billions of dollars (Joseph et al. 2008) and encourages studies to investigate other practical ways to obtain and analyze production yield (Table 12.1). Their potential also derives from research on these enzymes' cloning and expression in microorganisms. However, some negative points about lipases have been discussed since these enzymes are more efficient under moderate pH and temperature conditions. Therefore, they have much weaker enzymatic activity than chemical catalysts in high-temperature processes, increasing production costs and demanding longer processing time (Singh and Mukhopadhyay 2012). Lipases are widely used in detergents, pharmaceuticals, food (food additives), paper mills (to control the formation of residual hydrocarbons resulting from paper formulation), biopolymers, cosmetics, biodiesel, and biosensors (Anobom et al. 2014; Fleuri et al. 2014; Singh and Mukhopadhyay 2012). In addition, lipases resulting from hydrolysis reactions can be used to bioremediate oils and fats in oleo chemistry fields (Okino-Delgado et al. 2017; Nwobi et al. 2006).

3.1.2 Phytases

Phytases (EC 3.1.3.8, myoinositol hexaphosphate phosphohydrolase) can hydrolyze phytic acid into inorganic and myoinositol phosphate (Joshi and Satyanarayana

Table 12.1 Association between orange and grape waste obtainment processes and enzymatic production ways

Waste/processing type	Enzyme	Production way	Additional Information	References
Orange frit, peel, core (*Citrus sinensis* L. cv. Hamlin)/industrial	Lipase	Indirect: SSF[a] by *Aspergillus brasiliensis* and *A. niger*	Other fungal strains were used, and lipases were applied in different oil hydrolyses	Athanázio-Heliodoro et al. (2018)
Grape seed oil/industrial	Lipase	Indirect: LF[b] by *Aspergillus* sp.	Waste was added with vegetable oils used as carbon source	Tacin et al. (2019)
Orange frit, peel, core (*Citrus sinensis* L. Osbeck cv. Pear)/ industrial	Lipase	Direct: Fruit processed based on J. B. T. food tech	Waste was processed through mechanical crushing, frozen, lyophilized, and crushed again	Clarissa Hamaio Okino-Delgado & Fleuri et al. (2014)
Grape pomace/ industrial	Lipase	Indirect: SSF[a] by *Aspergillus ibericus*, *A. niger*, and *A. uvarum*	Winery waste was added with olive mill waste	Salgado et al. (2014)
Citrus peel/ manual	Phytase	Indirect: SSF[a] by *Humicola nigrescens* BJ82	Citrus peel was locally obtained, and fermentation was added with salts	Bala et al. (2014)
Orange pomace/ industrial	Phytase	Indirect: SSF[a] by *Paecilomyces variotii*	Industrial waste, fermentation added with salts and tannic acids	Madeira et al. (2012)
Citrus pulp/ industrial	Phytase	Indirect: SSF[a] by *Lichtheimia blakesleeana*	Waste processed for 2 h at 65 °C and subjected to ultraviolet light radiation for 2 h	Neves et al. (2011)
Citrus peel/ manual	Phytase	Indirect: SSF[a] by *Aspergillus niger*	Waste was washed, dried, separated based on particle size, and added with salts	Rodríguez-Fernández et al. (2010)
Orange peel/ manual	Protease	Indirect: SSF[a] by *Aspergillus brasiliensis*	10% of orange waste was added as carbon source	Chimbekujwo et al. (2020)
Grape pomace (cv. Cabernet Sauvignon)/ industrial	Protease	Indirect: SSF[a] by *Aspergillus niger*	Different combinations of grape pomace deriving from winery and wheat bran were tested	Papadaki et al. (2020)
Orange peel/ manual	Protease	Indirect: SSF[a] by *Aspergillus niger*	Orange waste was tested in separate and in combination to other substances, with emphasis on the combination to cottonseed meal	Castro et al. (2015)
Grape (*Vitis vinifera* L.)/manual	Protease	Direct: Overripe grapes were used	Aqueous extract prepared with the whole fruit	Koak et al. (2011)

(continued)

Table 12.1 (continued)

Waste/processing type	Enzyme	Production way	Additional Information	References
Orange peel/ industrial	Protease	Indirect: SSF[a] by *Bacillus* sp.	The fermentation filtrates were precipitated with 80% ammonium sulfate, after fermentation	Johnvesly et al. (2002)

[a] Solid-state fermentation
[b] Liquid fermentation

2015; Bohn et al. 2008) and can also catalyze phytate dephosphorylation and isomers formation. Phosphatase classes determined by IUPAC (International Union of Pure Chemistry) can be classified based on their region selectivity and enzymatic activity (de Bolster 1997). They can be called 3-phytase or 6-phytase, depending on the location of the first phosphate to be hydrolyzed (Selle and Ravindran 2007). Concerning optimal pH, phosphatases can be called histidine acid phosphatases (with pH around 5.0) or alkaline phytases (more significant activity at pH close to 8.0) (Baruah et al. 2007). Phytic acid (phytate) is the main phosphorus storage structure in vegetables. Still, it was considered an anti-nutritional component in the diet because it strongly chelates some cations and affects the absorption and digestion of minerals: calcium, copper, iron, magnesium, potassium, and zinc (Konietzny and Greiner 2003). In addition, several investigations have evidenced that phytate changes protein structures and modifies their behavior (O'Dell and Boland 1976). Phytates can also agglomerate with carbohydrates, forming insoluble complexes, which reduces their degradation and can become a potent noncompetitive inhibitor of the action of amylase (Selle et al. 2000). Therefore, phytase acts by mitigating the adverse effects and reducing eutrophication in aquatic environments since it reduces phosphorus released in the feces of aquatic animals (Vicente et al. 2019; Novelli et al. 2016; Jain et al. 2016).

Fruits generate different waste types from various plant parts (Table 12.1). Such diversity enables various applications, as well as direct and indirect phytase obtainment from different waste types.

3.1.3 Proteases

Proteases (EC 3.4, acting on peptide bonds) are enzymes that hydrolyze protein peptide bonds and act in the synthesis between the ester and amine bonds (Santos and Koblitz 2008). They are classified according to their cleavage points and catalytic site (Tavano 2013). They correspond to 60% of the world's enzymatic market and 25% of enzymes produced for industrial application (Novelli et al. 2016; Castro and Sato 2013; Ramakrishna et al. 2010). Like any other enzyme, the action of proteases is closely linked to biochemical conditions such as optimal temperature and pH ranges, enzymatic stability, affinity to and specificity of the substrate, and the active site. These aspects are relevant since they can compromise the enzyme's hydrolytic power (James et al. 1996). In addition, proteolytic enzymes mainly participate in numerous and complex metabolic processes, so they play an important role in protein catabolism, availability of hormones, defense mechanisms, intramembrane transport, blood clotting, tumor growth, gene expression regulation, and cell apoptosis (Konno et al. 2004; Poza et al. 2003; Walsh and Ahmad 2002; Godfrey and West 1996). These enzymes are used in the manufacture of beer, dairy products, and meat tenderizers (Castro and Sato 2013; Mazorra-Manzano et al. 2013); in leather processing; silk degumming; removal of animal skins in the textile industry; in the production of cleaning products for contact lenses; in the removal of silver in radiographic examinations; and in water and sewage treatment (Fornbacke and Clarsund 2013; Joshi and Satyanarayana 2013; Zambare et al. 2011; Pawar et al. 2009).

Table 12.1 presents some methodologies adopted to obtain lipases, phytases, proteases, and how waste was obtained based on manual or industrial processing. It is essential to emphasize the important role of studies in associating industrial chains with waste reusing since it can be a promising path for new products and a step further to strengthen green production cycles and enable a circular economy.

Industrial orange and grape waste (deriving from wineries) have shown promising potential to indirectly obtain lipases to be used as fermentation substrate and even directly used in orange waste. Orange waste deriving from manual and industrial processing has shown promising matrices for indirect phytase production; however, there are no records of grape waste used for phytase direct obtaining.

Proteases were obtained from both waste types; orange waste has the potential to be used as a substrate or additive in fermentation processes. On the other hand, grape waste appeared to be an efficient direct and indirect producer of underexplored plant proteases, whose enzymatic yield, associated with the low cost for obtaining it, can be a promising alternative for commercial protease production.

3.2 Biological Activity of Orange and Grape Waste

Bioactive compounds from agro-industrial waste can present several other biological activities besides enzymatic action. For example, orange and grape waste have antioxidant, antimicrobial, antidiabetic, antineoplastic, and anti-inflammatory action (Pereira et al. 2020; Saleem and Saeed 2020; Shahram et al. 2019; Hassan et al. 2019; Athanázio-Heliodoro et al. 2018; Cádiz-Gurrea et al. 2017; Pereira et al. 2017; Sharma et al. 2017; Xu et al. 2014; Clifton 2004), which are described below.

3.2.1 Antioxidant Activity

Reactive oxygen species (ROS) are unpaired oxygen-derived small molecules comprising oxygen radicals as superoxide, hydroxyl, peroxyl, and alkoxyl and non-radicals that are either oxidizing agents or easily converted into radicals, such as hypochlorous acid, ozone, singlet oxygen, and hydrogen peroxide. These molecules can play a complex role in cancer development by modulating different cell signaling pathways (Prasad et al. 2017; Halliwell 2007). They are naturally synthesized in aerobic organisms through cellular respiration; however, ROS accumulation is related to numerous multifactorial degenerative diseases such as Parkinson's, Alzheimer's, neoplasms, cardiovascular diseases, and diabetes, among others (Dávalos et al. 2004; Akpaffiong and Taylor 1998; Ames et al. 1993).

Compounds with antioxidant activity are extremely important to neutralize free radicals and reduce possible oxidative damage and, consequently, aging-associated diseases. Their action mode can be classified as (Shahidi and Zhong 2015):

(a) Primary antioxidants which prevent the reaction from occurring by making free radicals stable through hydrogen or receptors' donation.
(b) Secondary antioxidants inhibit oxidation by eliminating promoters, metal ions, and molecular oxygen, among others.

The antioxidant capacity of wastes (isolated and fermented) and their biomolecules can be measured by different methods, mostly:

(a) DPPH (2,2-diphenyl-1-picryl-hydrazil) – one of the most used tests based on salt radical consumption by a usually phenolic antioxidant compound (Kedare and Singh 2011).
(b) ABTS 2,2-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) – which is based on acid ammonium salt sequestration (Re et al. 1999).
(c) ORAC (oxygen radical absorbance capacity) – which is based on oxygen radical reduction, which supports its action in the peroxyl radical (Dávalos et al. 2004).
(d) FRAP (ferric reducing antioxidant power) – which has the potential to produce Fe^{2+} ions from the reduction of Fe^{3+} ions (Benzie and Strain 1996).

Orange waste is described in the literature as a strong antioxidant (Ozturk et al. 2018). This property results from more than 170 antioxidant substances found in citrus fruits (Zhou 2012).

Polyphenols or phenolic compounds are a large class of biologically active substances widely distributed among plants. They mainly constitute the secondary metabolism of plants, which accounts for their color and flavor, and protect them from pathogens and environmental adversities (Iranshahi et al. 2015). Phenolic acids and flavonoids stand among the most investigated phenolic compounds presenting antioxidant activity in citrus fruits (Zou et al. 2016).

Phenolic acids are often found in large amounts in citrus fruits; they present different free radical scavenging levels and have effective antioxidant properties to enable the dehydrogenation of hydroxyl groups (Zhou 2012).

Flavonoids play a direct role in eliminating free radicals, neutralizing lipid oxidation in vitro, and improving antioxidant enzyme activity in the body in vivo to decrease peroxide formation (Nakao et al. 2011). The two aromatic rings forming flavonoids' structure are linked to each other by three carbons that may, or may not, form a third ring, which differs from the other rings in oxidation degree and leads to flavonoids' subclassification as flavones, flavonols, isoflavones, flavanones, anthocyanin, and flavanols (Amiot et al. 2016). Flavonoids are overall found in their glycosylated form in plants since sugar molecules are determining factors for their function and bioavailability (Iranshahi et al. 2015). Hesperidin, naringin, and naringenin stand out among citrus flavonoids subclassified as flavanones (Zou et al. 2016).

Hesperidin is widely found in the epicarp, mesocarp, and endocarp of different citrus species; it can present antineoplastic (Devi et al. 2015), antidiabetic (Umeno et al. 2016), antimicrobial, and anti-inflammatory activity (Iranshahi et al. 2015).

Al-Ashaal and El-Sheltawy (2011) have analyzed hesperidin concentrations in *Citrus sinensis* (L.) Osbeck var. *Navel* (Rutaceae) orange peel and found that it is one of the main antioxidant agents observed in plants belonging to the genus *Citrus*.

Casquete et al. (2015) applied pressure treatments to sweet orange (*Citrus sinensis*) and to other citrus matrices (lemon, lime, and mandarin), which were purchased at a local supermarket and manually processed to extract phenolic compounds, as well as to measure their antioxidant and antimicrobial activity. Higher pressure treatment was associated with higher phenolic content; however, this treatment had different effects on different plant matrices, although it was associated with higher antioxidant activity measured through DPPH and ABTS. Orange peel extracts have shown the highest antioxidant activity against Gram-positive and Gram-negative bacteria; however, pressure treatments did not influence this biological activity.

Barrales et al. (2018) subjected orange peel obtained after fruit processing for juice production and essential oil extraction to pressurized and supercritical liquid extraction to evaluate different parameters, mainly phenolic compounds and antioxidant activity. Again, there was more remarkable hesperidin recovery, whose antioxidant activity was investigated based on the DPPH and FRAP methods.

Several other studies have reported the antioxidant activity of orange wastes. Ghosh et al. (2019) assessed the antioxidant potential of orange, mango, and pomegranate peel extracts, using DPPH and FRAPS methods. They found less expressive results for orange peel for both methodologies and no statistical difference for FRAP. Bier et al. (2019) analyzed the antioxidant potential of isolated and fermented orange waste by fungus species *Diaporthe* sp. using the ORAC, DPPH, and CUPRAC methods (antioxidant capacity to reduce cupric ions).

Citrus sinensis L. Osbeck (Navelate navel orange) and other citrus sources were obtained at a local market, manually processed, and submitted to phenolic compound extraction and antioxidant activity measurement. Results have shown that hesperidin was the compound most abundantly found in all peels; antioxidant activity was observed through the DPPH method and molybdenum reduction (antioxidant capacity activated by the complexation of phosphate and molybdenum). Furthermore, they showed that citrus peels could be used as sources of high added value polyphenols, whose overall processing cost at the industrial level can be minimized by obtaining these biomolecules, which have high commercial value and are applicable in the food, cosmetic, and health industries (Gómez-Mejía et al. 2019).

Grape fruits are rich in phenolic compounds, flavonoids, and stilbenes. The antioxidant activity reported for its waste is extensively explored in scientific studies. Tang et al. (2018) assessed the antioxidant capacity and phenolic and flavonoid composition of 30 varieties of grape seeds and skins. They identified several phenolic compounds (gallic acid, cyanidin-3-glucoside, epicatechin, catechin gallate, ferulic acid, rutin, and resveratrol) that contribute to such a biological action.

Antioxidant activity was also observed in Merlot berries (DPPH and FRAP assays) (Tinello and Lante 2017); in white and red grape peel subjected to different extraction processes (DPPH assay) (Vodnar et al. 2017); in red, black, and green grape seed extracts from Iran (DPPH assay) (Mirbagheri et al. 2018); as well as in grape seeds subjected to extraction process with different organic solvents (methanol, ethanol, chloroform, and acetone) (DPPH assay) (Hassan et al. 2019). The last two studies have correlated antioxidant activity to the amount and type of phenolic compounds.

The variety of phenolic contents and the difference in antioxidant activities in different waste types may be due to various conditions such as fruit ripening, climatic changes in cultivation, geographical origin, and storage conditions (Lasanta et al. 2014). Although there is research on the antioxidant activities and phenolic composition of grapes and their wastes (Orak 2007), there are still gaps in studies of wastes obtained close to the industrial reality.

Chowdhary et al. (2021) reported the generation of large amounts of waste in the viniculture system, accounting for environmental issues. The authors, as mentioned above, have emphasized the imperative need to obtain molecules from grape pomace by traditional and alternative processes to enable sustainable technologies. The reuse of this waste is also justified by the wide range of grape pomace applications, i.e., source of industrial enzymes, biochar, biopolymer, composite, feed, mushroom cultivation, single-cell protein, volatile organic compound, and bioactive compounds (neuro- and cardioprotective activities and activities against oxidative processes, bacteria, and diabetes were identified).

Grape seed extracts are rich in proanthocyanidins, which present an interesting and wide variety of biological activities. Catechins and gallates observed in these extracts can be precursors of proanthocyanidins, which act against oxidizing and inflammatory agents, harmful bacteria, and cancer. In addition, they can play a neuroprotective function, decrease lipid concentrations in the blood, and help regulate high blood pressure. Furthermore, they can be widely applied in the food industry. However, the small number of patents and commercial products comprising these extracts highlights the difficulty in transforming science into technology (product and/or process). Chen et al. (2020) have suggested that quantitative studies about the bioactivity of these extracts and their correlation to biological activity should be deepened to fill this gap and further expand their applications.

3.2.2 Antimicrobial Activity

The antimicrobial activity of orange and grape waste has been described for several pathogens. For example, Shahram et al. (2019) reported the antibacterial action of manually processed orange wastes against *Escherichia coli* and *Staphylococcus aureus*, commonly known to cause food poisoning. The Gram-positive bacteria were more sensitive to treatments than the Gram-negative ones.

On the other hand, Saleem and Saeed (2020) have used the agar well diffusion method to test the antibacterial activity of manually obtained orange peels and extracted through solvents (methanol, ethanol, ethyl acetate, and water). They observed that Gram-negative bacteria (*Escherichia coli*, *Klebsiella pneumoniae*, *Proteus vulgaris*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, and *Serratia marcescens*) were 20% to 30% more sensitive to extracts than Gram-positive strains (*Aeromonas hydrophila*, *Enterococcus faecalis*, *Lactobacillus casei*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Streptococcus pyogenes*). The study also compared aqueous extracts of orange, lemon, and banana peels in antifungal action on *Aspergillus niger*, *Candida albicans*, *Penicillium citrinum*, and *Saccharomyces cerevisiae*, which were ineffective for *P. citrinum* and *S. cerevisiae* and moderately effective for *A. niger* and *C. albicans* (Saleem and Saeed 2020).

Antimicrobial activity and phenolic profile studies were carried out with red and white grape waste treated, or not, through a thermal process. Better results were recorded against *S. aureus* strains, which were less resistant to the tested treatments (Vodnar et al. 2017). The tests were carried out in MIC (minimum inhibitory concentration), and MFC (minimum fungicidal concentration) was applied to *Bacillus cereus*, *E. coli*, *Enterococcus faecalis*, *Fusobacterium nucleatum*, *Listeria monocytogenes*, *Pediococcus aeruginosa*, *Pseudomonas anaerobius*, *S. aureus*, and *S. typhimurium*.

Besides, red grape waste recorded better results than white grape waste, correlated to polyphenol levels in the fruits. Antifungal activity against *Aspergillus flavus*, *Aspergillus niger*, *Candida albicans*, *Candida parapsilosis*, and *Penicillium funiculosum* was also tested, and grape waste has an action against *A. flavus*. The authors, as mentioned above, concluded that these waste types accounted for the highest antimicrobial activity values due to the high anthocyanin concentrations (Vodnar et al. 2017).

Green grape stems and peels have shown antifungal activity in *Candida* sp., *Microsporum* sp., and *Trichophyton* sp. In addition, based on the MIC method, flavan-3-ols (phenolic compound) found in grape waste were recently associated with antimicrobial activity (Simonetti et al. 2020; Pasqua and Simonetti 2016).

Soto et al. (2019) compared the antimicrobial capacity of orange and grape waste aqueous extracts and the silver nanoparticles (AgNPs) synthesized with these wastes to inhibit *E. coli* O157:H7 (ATCC 25922) and *L. monocytogenes* (ATCC 35152). The AgNPs produced with grape waste inhibited *E. coli*, and no difference of *L. monocytogenes* inhibition was observed between AgNPs obtained from orange and grape waste.

3.2.3 Antidiabetic Activity

Diabetes is a disease caused by insufficient production or inefficient insulin absorption, the hormone accounting for regulating blood glucose. This disease results from the complex multifactorial interaction of genetic, socioeconomic, and behavioral factors. According to the International Diabetes Federation, 463 million people have diabetes, approximately 1 in 11 adults aged 20 to 79 (IDF 2020).

China has the highest rates of diabetes: 116.4 million people are affected by the disease. Brazil ranks 5th, with 13 million diabetics, approximately 6.9% of the Brazilian population (Saeedi et al. 2019). Indicators point out that 10% (US$ 760 billion) of global expenditures with healthcare is related to diabetes (IDF 2020).

Diabetes types (I and II) are differentiated based on insulin production by the pancreas. Insulin is not produced, or few levels of it are released by beta cells in type I diabetes, also known as autoimmune disease. On the other hand, type II diabetes – which affects 90% of the diabetic population and is associated with weight gain – is defined as human body resistance to the insulin produced by the pancreas (Kerner and Brückel 2014).

Based on these premises, several studies have been conducted to find new alternatives to control diabetes, such as studies aimed at testing orange and grape waste. For example, Fayek et al. (2017) used citrus peels (*Citrus reticulata* Blanco cv. Egípcia), sweet orange (*Citrus sinensis* L. Osbeck cv. Olinda Valencia), white grapefruit (*Citrus paradisi* Macfad. Cv. Duncan), and lemon [*Citrus paradisi aurantiifolia* (Christm.) Swingle cv. Mexicano] to assess antidiabetic and hypocholesterolemic effects in tests carried out in vivo. The authors described that the most significant effects were correlated to the highest concentrations of nobiletin (polymethoxylated flavones) (Tsutsumi et al. 2014).

Muhtadi et al. (2015) conducted tests with 20 Wistar rats induced to diabetes to assess the antidiabetic activity of sweet orange peels at different daily doses (45, 125, 250, and 500 mg/kg body weight). The highest concentration of bark extract administered (500 mg/kg) after 15 days of treatment showed better results in reducing (61.36%) blood glucose levels.

Wheat cracker diets supplemented with 10% different orange peel were also assessed to observe the influence on blood glucose levels of diabetic rats. Baladi orange showed higher values for weight reduction and glycemic levels in animals among the four tested varieties (Baladi orange, Abo-Sora orange, tangerine, and Baladi lemon) (Youssef et al. 2013).

Doshi et al. (2015) used seed, skin, and stalk grape extracts (varieties Pusa navarang and Merlot) to assess the insulinotropic effect in rats. According to the authors mentioned above, the tested extracts have increased insulin secretion by pancreatic islets, which suggested a possible treatment for type II diabetes.

Cabernet Sauvignon peel extracts have also been reported as insulin production stimulants at different concentrations. This finding links these results to oleanolic acid, which is more abundant than anthocyanins and resveratrol in Cabernet Sauvignon grape peels (Zhang et al. 2004).

Patel (2015) found that new treatments against type II diabetes are related to dipeptidyl peptidase 4 (DPP4) inhibitors; thus, it was confirmed that procyanidins derived from grape seeds could modulate DPP4 activity and expression, based on inhibition assays conducted in vitro with human intestinal (Caco-2) cells and on experiments conducted in vivo with obese animals (González-Abuín et al. 2012).

3.2.4 Cell Modulation: Emphasis on Cytotoxicity

Research on cellular cytotoxicity provides information on the toxic behavior of cellular biochemical mechanisms. Cellular cytotoxicity was observed in hesperidin extracted from orange peels against liver (HPg2), breast (MCF7), cervix (HeLa), and larynx (HeP2) carcinomas based on the ELISA methodology. The results have shown high inhibition rates (IC50) for all cancer lines, mainly for laryngeal carcinogenesis (Al-Ashaal and El-Sheltawy 2011).

Studies carried out with silver nanoparticles and orange peels have shown cytotoxicity against lung cancer strains (A549) due to the induction of specific apoptosis during the cell cycle in G0/G1 (Annu et al. 2018).

The performance of citrus flavonoids such as tangeretin has been reported to induce apoptosis in human promyelocytic leukemia cells (HL-60). In addition, rodent tumor cells (L-929) die due to the action of flavonoids that stimulate TNF-α (tumor necrosis factor) to induce apoptosis (Manthey et al. 2001).

Nassiri-Asl and Hosseinzadeh (2016) performed a bibliographic review about the bioactive properties of grape waste; among them, anticancer effects and apoptosis induced in colon cancer strains were assigned to the grape seed of Italia and Palieri varieties (Dinicola et al. 2012). Furthermore, Derry et al. (2013) performed tests with grape seed extracts to induce apoptosis in colorectal cancer strains (SW480, SW620, and HCT116) and measured cytochrome C release; in addition to mitochondrial activity loss in carcinogenic cells, mediated cell death efficacy was found to be specific against colorectal cancer strain cells as it exhibited no toxicity in normal colon epithelial cells.

There was a correlation between the action of proanthocyanidins in increasing the radioelectric sensitivity of human liver carcinoma (HepG2), human cervical cancer (HeLa), and human leukemia cell line (K562) in X-ray images evaluated in vitro. Furthermore, high levels of proanthocyanidins against K562 were attributed to the modulating behavior of proanthocyanidins, which are found at the highest concentration (95%) in the seed of grape species *Vitis vinifera* (Pan et al. 2012).

Although the cytotoxic potential of orange and grape waste has been found in several experimental studies in animals and cellular tests, it is necessary to conduct clinical studies to confirm the action of active components in humans.

3.2.5 Anti-Inflammatory Activity

Inflammatory processes respond to cellular and tissue injuries featured by increased vascular permeability, cell flow at the site, and leukocyte migration (predominantly neutrophils), which eventually causes edema. Its main aim is to rule out the infectious agent through tissue destruction; therefore, chemical inflammation mediators (from plasma, cells of the endothelial and connective tissues, platelets, and leukocytes) are needed for such a purpose (Abbas et al. 2008).

Despite being a normal physiological process, people with autoimmune diseases and allergic responses cannot control the inflammatory response, making it necessary to administer anti-inflammatory compounds. After initial studies on the origin of these substances in plants (Salgado and Green 1956), many other researchers have succeeded in understanding the best extraction methods and mechanisms of inflammation action (Benavente-García and Castillo 2008; Manthey et al. 2001; Gábor 1979).

Recently, anti-inflammatory properties have been associated with flavonoids in citrus. Chen et al. (2017) compared orange peels (*Citrus reticulata*) from five different locations through Western blot and RT-qPCR assays. They found a correlation between high anti-inflammatory activity and high concentrations of polyphenols and flavonoids. Polymethoxylated flavones (PMFs) are potent TNF-α inhibitors, a class of cytokines secreted by macrophages capable of killing tumor cells (Manthey et al. 1999). The observed hesperidin, nobiletin, and tangeretin levels significantly increased the expression of anti-inflammatory properties (Ho and Kuo 2014; Londoño-Londoño et al. 2010).

Other studies pointed out that PMFs are responsible for the high anti-inflammatory effects shown in gene expression (Murakami et al. 2000). For example, Gosslau et al. (2014) performed tests in vivo on edema induced in mouse paws; they reported anti-inflammatory potential comparable to ibuprofen effects based on nutrigenomic analysis. Interestingly, PMFs are exclusively found in *Citrus* husks (*Citrus sinensis* and *Citrus reticulata*) (Gosslau et al. 2014; Li et al. 2006).

Grape seeds and skin are also reported as potential anti-inflammatory agents, but proanthocyanidins are the leading polyphenols; in this case, they showed high activity after tests applied to MCP-1 (monocyte chemoattractant protein-1) expression, which is a marker of vascular inflammation in human umbilical vein endothelial cells (HUVECs) (Cádiz-Gurrea et al. 2017).

Ferri et al. (2017) used white grape waste (*Vitis vinifera* L., mix of cultivars Trebbiano and Verdicchio) to obtain antioxidant, anti-tyrosinase, and anti-inflammatory actions in water- and alcohol-based solvent. Water-based extracts were more successful in decreasing the inflammatory response induced by TNF-α.

4 Conclusion and Future Perspectives

Orange and grape waste is generated in large amounts by industrial processing. In addition, several studies have focused on investigating the use of manual processing to obtain orange waste. However, proteases and phytases were not directly obtained from orange and grape waste so far. Thus, such a gap should be investigated to find new sources they can be obtained from and due to the wide range of applications of these enzymes. Waste types covered in this chapter also have great potential to obtaining antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and cell modulation compounds. Using waste to get enzymes and bioactive compounds based on direct and indirect bioprocesses can lead to green and clean technologies and enable maximum use of raw materials. In addition, products resulting from waste can have an exciting cost-benefit. Still, through research, it is necessary to correlate with the yield of biological activities with costs for confirmation and comparison with existing products.

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Chapter 13
Valorization of Fruit and Vegetable Waste: Yeast Fermentation

Gamze Nur Müjdeci and Kianoush Khosravi-Darani

Abstract The ever-increasing need for materials, energy, and water in the world and the ever-decreasing resources force the transition to a sustainable circular bioeconomy. Accordingly, there is an increasing interest in renewable resources and industrially important value-added bioproducts. Today, yeasts are an important tool for producing value-added bioproducts from renewable resources through the fermentation process. Fruit and vegetable wastes (FVWs), which cause soil and water pollution, greenhouse gas emissions, and economic losses, have a very high potential to be used as a substrate source due to their nutritional components. The evaluation of FVWs as a substrate also contributes to the zero waste policy, which is becoming increasingly widespread in the world. Some of the natural bioproducts produced by yeasts using FVWs are enzymes, color and flavoring agents, biopolymers, single-cell proteins, and fuels. These products are widely used in food, chemical, biomedical, and many other industries. This chapter focuses on the potential of FVWs to be converted into value-added products through fermentation by yeasts and the importance of this process for global industry, human health, environmental protection, and the economy.

Keywords Fruit and vegetable wastes · Biocolor · Biofuels · Aroma · Yeasts · Fermentation · Value-added products

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1 Introduction

The United Nations General Assembly has designated 2021 as the International Year of Fruit and Vegetables. The scope of the International Year of Fruit and Vegetables 2021 highlights the role of fruits and vegetables in human nutrition, food safety, health, and the evaluation of fruit and vegetable wastes (FVWs). One of the UN Sustainable Development Targets is "Target 12.3: by 2030, halve the per capita global food waste at the retail and consumer level, and reduce food along production and supply chains including postharvest losses" (Fabi and English 2019). To achieve this target, countries must create a national strategy and development plan, and nongovernment organizations and academic and various state institutions are mobilized. Decreased energy, soil, and water resources, increased agricultural waste, environmental pollution, greenhouse gas emissions, and economic losses play a significant role in this mobilization.

The "waste biorefinery" approach, which has become popular recently, aims to obtain value-added products from agricultural wastes through various bioprocesses. The International Energy Agency defines biorefining as "the sustainable processing of biomass into a spectrum of biobased products (food, feed, chemicals, materials) and bioenergy sources (biofuels, power and/or heat)" (Liu et al. 2021). Again, the increasingly widespread concept of "circular bioeconomy" refers to the gradual use of biomass from biological sources into a systematic approach to economic development (Leong et al. 2021). A circular bioeconomy supports biorefining and ensures the efficient use of biomass, including waste and by-products, for the sustainable production of value-added products such as food, biomaterials, feed, and bioenergy (Leong et al. 2021).

FVW biorefinery support the bioeconomy. Loss of fruits, vegetables, roots, and tubers mostly occurs during primary production, ranging from 10% to 30% of the total output (Joensuu et al. 2021). In the studies conducted for EU countries, it has been revealed that 50% of household food wastes are FVWs (De Laurentiis et al. 2018). The total food loss resulting from the agricultural production step in the food supply chain in Turkey is approximately 13.7 million tons, which constitutes 11.9% of the food produced. It has been stated that about 9.48 million tons of fruit and vegetables were lost during agricultural production in Turkey in 2016. This loss constitutes 20% of the food produced in Europe, North America, and Latin America (Salihoglu et al. 2018). In 2016, it was stated that approximately 3.38 million tons of fruit and vegetables were lost during postharvest handling and storage in Turkey, which corresponds to 8% of production (Salihoglu et al. 2018). In Iran, it has been reported that 85% of the 82 million tons of food need per year is provided by agriculture, and 35% of this, 28 million tons, is wasted. This loss is approximately six times the world average of food waste (Abadi et al. 2021). India is the world's second-largest producer of fruits and vegetables (Panda et al. 2016). It has been reported that 18–30% by weight of total fresh horticultural products produced in India in 2015–2016 turned into waste due to inadequate transportation and storage (Mozhiarasi et al. 2019).

Fig. 13.1 Yeast as a single-celled biorefinery, *, Single-cell protein

FVWs are generally evaluated as animal feed. However, for a sustainable bioeconomy, it is becoming increasingly important to assess the production of high value-added products from these wastes. One of the methods to be used for this purpose is fermentation technology. Yeasts are among the first microorganisms used in fermentation to produce valuable compounds for medicinal, nutritional, and industrial applications (Sabater et al. 2020). Yeasts produce a wide variety of extracellular enzymes, antibiotics, pigments, polysaccharides, and oils, so their potential to be used in the evaluation of FVWs is relatively high. The importance of yeast as a single-celled factory in the biorefinery approach (Fig. 13.1), the potential of using FVWs as substrates in yeast fermentation, and the high value-added products produced using these substrates will be explained in more detail in this chapter.

2 Biorefinery Approach in a Circular Bioeconomy

The concepts of biorefinery and circular bioeconomy, whose definitions are given in Section 1, are detailed. Then, the importance of the biorefinery approach in the circular economy is presented with examples.

An example of this is the conversion of winery waste to biorefinery within the circular economy framework (Ncube et al. 2021). According to the International Organization of Vine and Wine report, the total grape production in the world in 2019 was 77.8 MT, and 57% of the total grape production is used in wine production. According to the same report, the highest amount of wine production globally is realized in Italy, France, and Spain, respectively. The amount of wine production in the world in 2019 was 257 million hectoliters (MHL). On the other hand, the consumption amount was 241 MHL (International Organization of Vine and Wine 2020). Therefore, it is important to evaluate the high amounts of waste that arise due to the widespread use and production of wine globally and transform them into value-added products.

Wine industry wastes include grape skin, stem, tartar, and pomace. The winery waste, called "vinasse," is the largest amount of waste and consists of various wastewaters and is a significant threat to environmental pollution as it contains persistent compounds and organic acids. The high organic components of vinasse make it widely used in biogas production (Parsaee et al. 2019). The review article of Parsaee et al. (2019) emphasized that the use of vinasse in biogas production has several advantages. In summary, these are:

- Reduction of the effects of toxic gases such as sulfur dioxide and nitrogen oxides
- Reusability of the steam produced as a result of the complete combustion of biogas in boilers
- Possibility to use one-third of the produced biogas as fuel
- The possibility of using the produced biogas in vehicles and city buses
- Possibility of using the produced biogas in combined heat and power systems
- Possibility of using the produced biogas as a power source in alcohol-producing reactors or as an energy source in the drying of yeasts
- Opportunity to use instead of diesel in agricultural machinery

While Tena et al. (2020) used vinasse for hydrogen production, Araujo and Oliveira (2020) investigated its use for electricity generation. There are also studies investigating the use of vinasse in the production of fertilizer (Siuris et al. 2016), lactic acid (Liu et al. 2010), methane (García-Depraect et al. 2020), biosurfactant (Oliveira and Garcia-Cruz 2013), lipid (Fernandes et al. 2017), tartaric acid (Salgado et al. 2010), and biocontrol agent (Bai et al. 2008; Santos et al. 2008).

Grape marc, another winery waste, has been studied in terms of lactic acid, biosurfactant, bio-emulsifier, tannin, polyphenol, anti-allergen, hydrolytic enzyme, bioethanol, and plant substrate production and its use as a microbial and human food source, protein, and biocontrol agent (Devesa-Rey et al. 2011).

Industrial wastes based on potato (*Solanum tuberosum* L.) and sweet potatoes (*Ipomoea batatas*) are likely to be evaluated by another biorefinery approach. Potatoes are one of the most produced and consumed vegetables worldwide (Pathak et al. 2018). According to FAOSTAT 2019 data, the largest potato and sweet potato producer in the world is China, with a production of approximately 92 and 52 million tons, respectively. In potato production, China is followed by India (50 million tons), the Russian Federation (22 million tons), Ukraine (20 million tons), and the United States (19 million tons) (FAOSTAT 2019). Potatoes are consumed fresh and in the food industry in the production of a wide variety of products such as chips, fried potatoes, frozen potatoes, canned goods, flour, and starch. Because of this widespread use, large amounts of waste are produced. These wastes are potato skins, over-fried pieces, tiny, chipped pieces, and wastewater. Potato skins make up 15–40% of the initial product mass, depending on the peeling method (Torres and Domínguez 2020). Potato processing industries worldwide generate 70–140 thousand tons of potato skins annually (Alrefai et al. 2020). Flesh remaining from starch extraction and wastewater is another high-volume potato industry waste, accounting for 75% of the initial product mass (Torres and Domínguez 2020). Rotten potatoes are a waste of potato cultivation and makeup 5–20% of the entire crop (Afifi et al. 2011).

When the researches were examined, it was seen that potato wastes were widely used for bioethanol production. One of these was conducted in 2011, and waste from a local potato industry in Egypt was evaluated for bioethanol production (Afifi et al. 2011). Arapoglou et al. (2010) produced ethanol from potato peel. Izmirlioglu and Demirci (2012) produced ethanol from waste potato mash and Abanoz et al. (2012) from potato processing wastewater. Along with current needs, the purposes of the evaluation of wastes are also changing. The current COVID-19 pandemic has increased the demand for alcohol along with the need for disinfection. In a study conducted in 2020, the production of ethyl alcohol and alcohol-based hand sanitizer from sweet potato waste (rotten sweet potato, peel, and pulp) was evaluated from a techno-economic point of view. In the study above, it was highlighted that the production of 1342 L alcohol-based hand sanitizer per day could meet the urgent market needs in the face of the COVID-19 pandemic crisis; the use of waste potatoes for disinfectant production will contribute to reducing greenhouse gas emissions and saving landfill costs, thus achieving the goals of a circular bioeconomy (Weber et al. 2020).

Potato and sweet potato wastes have also been used to produce antioxidants, enzymes, phenolic compounds, colorants, dietary fiber, medical substances, and various chemicals (Al-Weshahy and Rao 2012). Potato skins were studied for antimicrobial activity and their potential to be used as antioxidants in producing active edible films (Gebrechristos et al. 2020). The inhibition effect of the films produced in this study on *Escherichia coli*, *Salmonella enterica*, and *Staphylococcus aureus* was determined. In addition, it was reported that potato peel extract could be used as an alternative technology for active food packaging by combining it with potato starch (Gebrechristos et al. 2020). Studies are also available for the production of enzymes such as glucoamylase (Izmirlioglu and Demirci 2015), phytase (Tian and

Yuan 2016), amylase (Mushtaq et al. 2017), carboxymethylcellulase, filter paperase, and xylanase from potato bagasse (Dos Santos et al. 2012).

Examples can be multiplied for the biorefinery approach in the circular bioeconomy. Today, stochastic models in which biomass is converted into high value-added products show that the biorefinery approach will become widespread at the industrial level in the future when a detailed cost-benefit analysis is made.

3 Yeasts as Biofactories

Today, to increase the efficiency of biotechnological products, the isolation and identification of new yeast strains and their controllable design with synthetic biological methods have gained importance.

Saccharomyces cerevisiae is one of the leading industrial microorganisms used to produce biochemicals and is the most extensively studied unicellular eukaryote (Kavšček et al. 2015). The fact that *S. cerevisiae* has GRAS (generally regarded as safe) status and is an excellent source of B vitamins, proteins, nucleic acids, and minerals also increases the use of this species in the human diet. *S. cerevisiae* is also known for its fermentative effect, used in wine and beer production (Rubio et al. 2020). *S. cerevisiae* is the most widely used microorganism for bioethanol production due to its high production rate (Evcan and Tari 2015). Ethanol production was reported from apple pomace by solid-state fermentation using *S. cerevisiae* (Joshi and Attri 2006).

Studies have shown that mutant *S. cerevisiae* strains produce red pigment (Amen et al. 2013; Jainarayanan et al. 2020). Mutations in the *ADE1* or *ADE2* genes of *S. cerevisiae* cause a characteristic red pigment deposition in the vacuole of this yeast under adenine-limiting conditions (Jainarayanan et al. 2020). Mutants of *S. cerevisiae* were also used to produce lycopene, a red carotenoid pigment with antioxidant and potential anticancer activity, widely used in the food, feed, and cosmetics industries as a natural colorant and pharmaceutical (Hong et al. 2019).

Genetically engineered *S. cerevisiae* strains have been used successfully to produce squalene (a type of lipid). Since squalene is a natural antioxidant that can protect cells from free radicals and reactive oxygen species, it is essential for both the human body and cosmetics and possible pharmaceutical industry applications (Paulino et al. 2017). Some other metabolites produced naturally or by metabolic engineering of *S. cerevisiae* are schematized in Fig. 13.2.

Yarrowia lipolytica is one of the other most studied yeasts due to its oleaginous property, heterologous protein expression, polyol, and organic acid production. The fact that *Y. lipolytica* is GRAS ensures its widespread use in the food and pharmaceutical industries (Mirończuk et al. 2016). This yeast can assimilate several carbon sources used for identification but have the unique ability to metabolize hydrophobic substrates such as oil, fatty acids, and n-alkanes (Rywińska et al. 2013). Some industrially important components produced by *Y. lipolytica* are sugar alcohols such as erythritol and mannitol, which are natural sweeteners; organic acids such

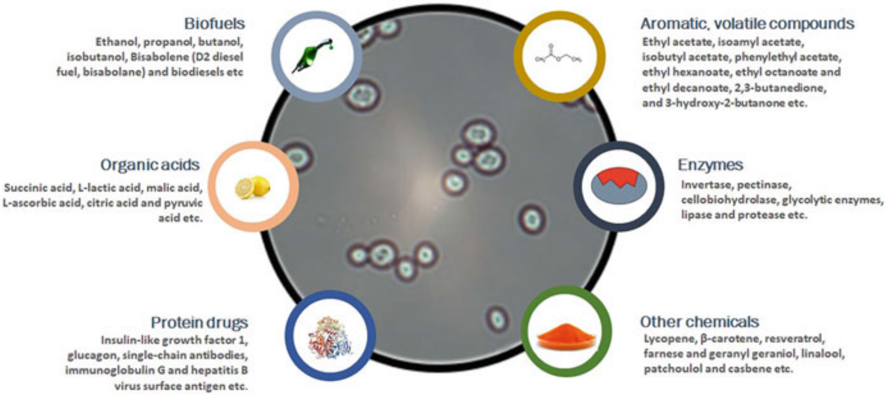

Fig. 13.2 Products synthesized by wild and/or recombinant *Saccharomyces cerevisiae*

as isocitric, α-ketoglutaric (α-KGA), pyruvic, succinic, and citric acids; oleochemicals; and enzymes such as proteases, lipases, Rnases, esterases, and phosphatases (Rywińska et al. 2013; Zinjarde 2014; Magdouli et al. 2017).

Glycerol can be an important source of substrate for *Y. lipolytica* (Mirończuk et al. 2016). In research, 27 strains of *Y. lipolytica* were screened for citric acid production in media containing glycerol. All *Y. lipolytica* strains could produce citric acid at varying concentrations (Levinson et al. 2007). Furthermore, both citric acid and oil production occur in nitrogen-limited media containing glycerol (Papanikolaou and Aggelis 2002).

Rhodotorula glutinis is an oleaginous red yeast that produces valuable metabolites such as lipid and β-carotene. β-carotene is a precursor of vitamin A and exerts many important biological effects such as antioxidant and anticarcinogenic activities and immunomodulation (Saenge et al. 2011). In addition, *R. glutinis* has the advantage of being able to grow on oily substrates. In a study, lipid and carotenoid production was realized by *R. glutinis* by using wastewater from potato, fruit juice, and lettuce processing (Schneider et al. 2012).

Aureobasidium pullulans is another single-celled factory that produces many industrially important enzymes and metabolites. This species produces lipase, amylase, cellulase, xylanase, protease, laccase, mannose, β-glucosidase, pectinase, β-fructofuranosidase, glucose oxidase, and glucanase. *A. pullulans* also produce aroma compounds such as 2-methylbutanoic acid, 3-methyl-1-butanol, and ethyl octanoate and polyesters such as poly-(β-L-malic acid) (Chi et al. 2009; Pitt and Hocking 2009; Singh 2015; Bozoudi and Tsaltas 2018). *A. pullulans* can be used as a single-cell protein source and produce some antimicrobial compounds. The most important biotechnologically important metabolite of *A. pullulans* is pullulan.

Several yeasts used for metabolite production in the literature and the value-added products they produce are given in Table 13.1.

Table 13.1 Yeasts investigated for metabolite production in the literature and their value-added products

Species/strain	Substrate	Metabolite	Reference(s)
Aureobasidium pullulans AY82	Xylose and hemicellulose hydrolysate	Pullulan	Chen et al. (2014)
Aureobasidium pullulans	L-DOPA	Melanin and	El-Bialy et al. (2019)
		antifungals (fluconazole and itraconazole	
Candida bombicola ATCC 22214	Glucose, yeast extract, urea, and lipid precursor	Sophorolipid	Felse et al. (2007)
Candida famata	Sucrose, lactose, maltose, glycerol, or sorbitol	Exopolysaccharide	Gientka et al. (2016)
Candida guilliermondii			
Candida guilliermondii FTI 20037	Hydrolyzate of sugarcane pressings, sugarcane bagasse	Xylitol	Hernández-Pérez et al. (2016), Vaz de Arruda et al. (2017)
Candida sorbosivorans SSE-24	Glucose and yeast extract	Erythritol	Saran et al. (2015)
Yarrowia lipolytica A UV'1	Crude glycerol		Tomaszewska et al. (2012)
Yarrowia lipolytica Wratislavia K1			
Yarrowia lipolytica A-15			
Candida tropicalis ATCC 20115	Glucose and fructose	Citric acid	Kim et al. (2015)
Candida oleophila ATCC 20177			
Candida oleophila ATCC 20373			
Candida zeylanoides ATCC 20367			
Yarrowia lipolytica Wratislavia AWG7	Crude glycerol solution		Rywińska and Rymowicz (2010)
Candida tropicalis ATCC 13803	Glucose and xylose	Ethanol	Kim et al. (1999)
Candida guilliermondii FTI 20037	Glucose		Wen et al. (2016)
Candida shehatae NL33	Konjac hydrolysate		Zhao et al. (2020)
Candida rugosa CBS 6330	Yeast extract or peptone	Lipase	Fadiloğlu and Erkmen (2002), Kim and Hou (2006)

(continued)

Table 13.1 (continued)

Species/strain	Substrate	Metabolite	Reference(s)
Candida cylindracea NRRL Y-17506	Oleic acid		
Candida boidinii No.2201	Yeast extract, peptone, and glucose	L-lactic acid	Osawa (2009)
Candida boidinii KY2132			
Candida tropicalis UCP 1613	Whey, cassava waste-water, and soybean post-frying oil	Biosurfactants	Daylin et al. (2017)
Cryptococcus sp.YLF	Several substrates including oils		Derguine-Mecheri et al. (2018)
Cryptococcus curvatus ATCC 20509	Hemicellulose prehydrolysate liquor	Lipid	Samavi et al. (2019)
Cryptococcus podzolicus DSM 27192	Glucose	Gluconic acid	Qian et al. (2019)
Hansenula polymorpha HpPen1	Phenylacetic acid	Penicillin	Gidijala et al. (2009)
Schizosaccharomyces pombe ARC010-1	Glucose	Ricinoleic acid	Holic et al. (2012)
Saccharomyces cerevisiae TAM	Glucose	Succinic acid	Yan et al. (2014)
Saccharomyces cerevisiae SR8	Xylose	Isobutanol	Lane et al. (2020)
Saccharomyces cerevisiae CEN.PK2-1	Dextrose	Resveratrol	Sydor et al. (2010)

4 FVW Composition and Their Substrate Potential

FVWs can be categorized according to their quality and point of origin in the food supply chain (Panda et al. 2016). FVW typically contains 85% moisture and 10% solids and is rich in organic compounds (Edwiges et al. 2018). According to Esparza et al. (2020), waste fruits have higher total solids (TS), volatile solids (VS), and C/N ratios than vegetable wastes. While the TS of fruit wastes is between 7.5 and 23% on a fresh weight basis, that of vegetables is 3–11%. While VS is found at the rate of 5–12% in fruit wastes and 2–9% in vegetable wastes, the C/N ratio of fruit wastes is 19–53% and vegetables is 10–21% (Esparza et al. 2020).

One of these wastes, apple pulp, represents approximately 25–35% of the weight of fresh apples processed with various industrial applications (Evcan and Tari 2015). Apple pomace is rich in starch, sucrose, fructose, glucose, cellulose, hemicellulose, pectin, magnesium, calcium, quercetin, procyanidin (flavonoids), and phenolic acids (Rodríguez-gómez et al. 2017; Okoro and Shavandi 2021). In addition, this waste has a moisture content of 40–82.7% (Okoro and Shavandi 2021).

Grape pulp is a waste consisting of seeds, skins, and stems. The skin and seeds represent approximately 38–52% and 5–10% of the pulp, respectively (Beres et al. 2017). Grape pulp containing fiber and oil is also rich in bioactive compounds such as phenolic compounds. The most abundant phenolic compounds in wine pulp are flavonols (56–65% of total flavonols) (Beres et al. 2017). The monosaccharide composition of grape pomace is rhamnose, arabinose, xylose, mannose, galactose, glucose, uronic acid, and galacturonic acid (Beres et al. 2017).

Since tomato is one of the most produced vegetables in the world, the amount of tomato waste is also high. In industrial applications of tomatoes, 7.0–7.5% of the raw material is wasted, and these wastes consist of peels, seeds, fibrous parts, and pulp residues (Nour et al. 2018). Tomato pulp consists mainly of skin and seeds and contains 25.4%–50.0% fiber, 15.4%–23.7% protein, 5.4–20.5% oil, and 4.4–6.8% mineral matter on a dry matter basis (Valle et al. 2006).

Onion is another important vegetable grown worldwide (Cho et al. 2021). Approximately 37% of onions are produced as waste, including onion skins, two outer fleshy scales, roots, upper and lower parts of onions, and undersized, malformed, diseased, or damaged onions (Sharma et al. 2016). Onion waste consists of total phenolics, flavonoids, flavonols, antioxidants, and other phytochemicals. In addition, onion waste contains high amounts of minerals (in the lower and upper roots), sulfur, and carbohydrates as principal components (Sharma et al. 2016). Untreated onion wastes contain sucrose, glucose, fructose, rhamnose, arabinose, xylose, mannose, and galactose, among which sucrose, glucose, and fructose are dominant (Cho et al. 2021). The nutritional components of various other FVWs are presented in Table 13.2.

5 Novel Value-Added Products Synthesized by Yeast From FVWs

There are several novel value-added products developed from FVWs by yeast fermentation.

5.1 Pigments

Pigments are used in food, cosmetics, textiles, and many other industries. The food colorant market is expected to reach US$4.3 billion by the end of 2021 and grows at a compound annual growth rate (CAGR) of 4.7% to reach US$5.4 billion by 2026 (https://www.marketsandmarkets.com). This growth in the pigment market causes the search for new production sources. For example, yeasts are an excellent source of microbial pigments compared to bacteria and fungi due to their high growth rate (Panesar et al. 2015).

Table 13.2 Chemical and nutritional composition of some fruit and vegetable wastes (% of dry matter)

Waste/by-product	Moisture	Ash	Protein	Fat	Crude fiber	Total carbohydrates	Reference
Almond fruit waste (exocarp)	11.84	6.75	4.16	4.00	27.50	nd*	Annongu et al. (2006)
Beet molasses	19.1–33.0	6.5–18.5	10.7–15.6	nd*	nd*	50.6–68.4	Palmonari et al. (2020)
Cane molasses	20.4–24.3	10.2–16.3	2.22–9.31	nd*	nd*	57.0–71.0	Palmonari et al. (2020)
Carrot waste (damaged, rotten, nonedible parts)	81.2	2.11	1.52	<0.01	6.34	8.8	Zhivkova (2020)
Melon husk	2.42	7.73	19.14	1.71	8.12	61.01	Ogbe and George (2012)
Melon seed	5.32	4.05	29.90	35.36	19.52	5.85	Mian-Hao and Yansong (2007)
Olive waste cake	3.86–4.65	572–6.73	6.24–8.62	4.59–9.11	29.11–37.27	71.50–78.10	Uribe et al. (2015)
Orange bagasse	78.21	3.39	19.78	nd*	nd*	nd*	Cypriano et al. (2018)
Pepper waste (damaged, rotten, nonedible parts)	93.2	0.26	0.75	<0.01	1.48	4.3	Zhivkova (2020)
Potato peel	85.06	6.34	8	2.6	nd*	68.7	Arapoglou et al. (2010)
Potato pulp	87	4	4	nd*	7	nd*	Kot et al. (2020)
Raw potato peel	83.3–85.1	0.9–1.6	1.2–2.3	0.1–0.4	nd*	8.7–12.4	Sepelev and Galoburda (2015)
Sweet potato leaves	87.37–90.27	13.43–16.99	28.01–38.52	2.49–4.28	9.26–11.4	30.13–42.64	Hong et al. (2020)
Watermelon rind	93.3	2.55	17.23	1.05	nd*	83.9	Mendez et al. (2021)

*No data

Monascus yeasts produce yellow (monascin and ankaflavin), red (monascorubramine and rubropunctamine), or orange (monascorubrin and rubropunctatin) colored pigments that can be used to color foods (Lv et al. 2017). The pigment synthesized from polyketide chromophores and β-keto acids by esterification has been used as a natural colorant and traditional natural food additive in East Asia (Kim et al. 2002). In addition, monascus pigment has many health benefits such as anticancer, antimicrobial, anti-inflammation, antiobesity, and antidiabetes. This pigment is produced by both solid-state fermentation and submerged fermentation (Feng et al. 2012).

In a study, monascus pigment was produced with solid-state fermentation using jackfruit seed powder or palm kernel cake as substrate using *Monascus purpureus* LPB 97 strain (Babitha et al. 2007). In another research in which orange peels were used as a substrate, the pigment was synthesized by *M. purpureus* ATCC 16365 strain (Kantifedaki et al. 2018).

Carotenoids are red, yellow, and orange color pigments commonly found in fruits, flowers, roots, seaweeds, invertebrates, fish, birds, bacteria, fungi, and yeast and are used as colorants in the food industry (Ribeiro et al. 2011). According to Business Communications Company Research, β-carotene has the largest share in the global carotenoid market, with a value of more than $300 million by 2018 (Pi et al. 2018). β-carotene is also used as a dietary supplement, the primary source of pro-vitamin A (Ribeiro et al. 2011). This pigment is also known to be an antioxidant with anticancer, anti-disease, and immune-enhancing properties and has the functions of improving human immunity and preventing tumors, thrombosis, atherosclerosis, and aging (Wang et al. 2008).

Some yeast species known to be β-carotene producers are *Sporobolomyces roseus*, *Rhodotorula glutinis*, *Rhodotorula graminis*, *Rhodotorula acheniorum*, *Rhodotorula toruloides*, *Sporidiobolus salmonicolor*, and recombinant *S. cerevisiae* (Buzzini et al. 2005; Verwaal et al. 2007; Maldonade et al. 2008; Wang et al. 2008; Nasrabadi and Razavi 2011). In a study, β-carotene was produced in fermented radish brine using *R. glutinis* DM28 strain (Malisorn and Suntornsuk 2008). In another study, inedible parts of oranges, sweet lemons, bananas, and mangoes were used for β-carotene production by *R. toruloides*, *R. glutinis* Y1, and *R. glutinis* ab1 strains (Sinha et al. 2021).

Melanin is another well-known pigment produced by all organisms (Pralea et al. 2019). Typically, melanin is dark brown or black in color (Almeida-Paes et al. 2012). This pigment protects the microorganism from various adverse environmental conditions. Several melanin types are known in nature, and melanin is produced by fungi, which is 1,8-dihydroxynaphthalene synthesized from acetyl-coenzyme A via the polyketide pathway (Pombeiro-Sponchiado et al. 2017). *Kluyveromyces marxianus*, *Streptomyces chibanensis*, *Aspergillus* sp., *Wangiella dermatitidis*, *Burkholderia cepacia*, *Cryptococcus neoformans*, *Exophiala dermatitidis*, *Fonsecaea pedrosoi*, *Sporothrix schenckii*, *Histoplasma capsulatum*, *Paracoccidioides brasiliensis*, *Candida albicans*, *Pneumocystis jirovecii*, *Scytalidium dimidiatum*, and *A. pullulans* are among the best-known melanin-producing fungi, yeast, and yeast-like fungi species.

Table 13.3 Production of yeast pigments from fruit and vegetable wastes

Fruit/ vegetable waste	Yeast	Pigment	Reference(s)
Fruit waste extract	*Xanthophyllomyces dendrorhous* *Rhodotorula rubra* 1446	Astaxanthin Carotenoid	Korumilli et al. (2020)
Sugarcane baggasse	*Monascus purpureus*	Red pigment	Silveira et al. (2013) and Moussa et al. (2018)
Potato peel	*Monascus purpureus* NRRL 1992	Red pigment	Moussa et al. (2018)
Onion peel Pea pods Potato peel	*Rhodotorula mucilaginosa* MTTCC 1403	Carotenoid	Sharma and Ghoshal (2020)
Cassava wastewater	*Rhodotorula glutinis*	Carotenoid	Ribeiro et al. (2011)

Melanin has broad application potential in the agriculture, cosmetics, and pharmaceutical industries (El-Gamal et al. 2017). There are many studies on the production of melanin using pineapple, orange, and pomegranate waste, corn liquor, grape waste, corn maceration liquid, jackfruit seed, coconut pulp, molasses, sunflower husk, millet, banana stalk, and sugarcane pulp hydrolysates (Tarangini and Mishra 2014; Santhanalakshmi et al. 2017). Some other examples of pigments that were previously produced by yeast using FVWs are given in Table 13.3.

5.2 *Enzymes*

Enzymes are biological catalysts responsible for various metabolic processes (Panda et al. 2016). Enzymes are used in many fields, especially in the food, biofuel, paper, and textile industries. According to the Industrial Enzyme Market Report, the value of the industrial enzyme market was over $6300 million in 2020. In the 2021–2026 periods, the enzyme market is expected to register a CAGR of more than 6%. According to the report, the food industry is the largest source of income for the enzyme market in 2020, followed by animal feed, detergent, and biofuel industries.

Many studies are using FVWs in enzyme production. Examples of these wastes are potato, carrot, orange, pineapple, papaya, and banana peels; tomato, apple, grape, and lemon peel pulp; passion fruit, melon, and watermelon waste; date waste; and olive oil cake (Botella et al. 2005; Shukla and Kar 2006; Alkan et al. 2007; Khosravi-Darani and Zoghi 2008; Martínez Sabajanes et al. 2012; Moftah et al. 2012; Zilly et al. 2012; Qureshi et al. 2017).

Although it is seen in the literature that mainly molds and bacteria are used in enzyme production, there are also studies in which yeasts are used. Yeast species used for this purpose include *A. pullulans*, *Bullera alba*, *Candida robusta*, *Candida* *santjacobensis*, *Cryptococcus humicola*, *Cryptococcus laurentii*, *Debaryomyces occidentalis*, *Debaryomyces polymorphus*, *Filobasidium floriforme*, *Sporococcus occidentalis*, *Kodamaea ohmofioleumiosis*, *Salmonomycea husmazodiosis*, *Sporidiobolus pararoseus*, and *Y. lipolytica* (Chi et al. 2007; Bussamara et al. 2010; El Enshasy and Elsayed 2017).

In one study, lipase was produced by the *Candida cylindracea* NRRL Y-17506 strain in olive mill wastewater (D'Annibale et al. 2006). In another study, mango seed and peel were used as waste for lipase production, and *Y. lipolytica* IMUFRJ 50682 strain was used as the microorganism (da S. Pereira et al. 2019). In a study by De Almeida et al. (2016), the lipase production capacity of *Candida viswanathii* was investigated in fermentation media using cassava peel, sugarcane bagasse, or citrus pulp as substrate (De Almeida et al. 2016). While lipase production was not observed in the medium where cassava peel was used, it was stated that the lipase activity was close to each other in the media where sugarcane bagasse and citrus pulp were used. Yeast species investigated in this study include *Candida lipolytica* NRRL Y-37-1, *C. albicans* NRRL Y-12, *C. guilliermondii* NRRL Y-2075, *Pichia pinus*, *Cryptococcus albidus* NRRL Y-1400, *K. marxianus* NRRL Y-7571, *K. marxianus* 8281, and *S. cerevisiae* NRRL Y-2632. It has been reported that *C. guilliermondii* has the highest protease activity among these yeasts. In another study, pectinase production was investigated by *S. cerevisiae* PVK4 strain from orange peel, mango peel, grape peel, sapodilla (*Manilkara zapota*) peel, banana peel, apple pomace, papaya peel, and pomegranate peel. The highest pectinase amount was 929 U/mL, produced in experiments using grape and banana peels as substrate sources (Poondla et al. 2016).

5.3 Aroma Compounds

Aroma components are substances that have widespread use, especially in the food industry. These components can be extracted from plant and animal sources (natural) or produced synthetically (artificial). Yeasts produce natural aroma components with enzymes such as lipase, protease, and esterase during fermented food production. Products such as wine, beer, fermented vegetables and fruits, and vinegar are flavored by microorganisms, including yeast. In some cases, yeasts can cause undesirable taste and odor in foods. Aroma compounds produced by yeast fermentation include glycerol, aldehydes, alcohols, propanediol, organic acids, isoprenoids, esters, and steroids. Yeasts such as *C. tropicalis* and *Y. lipolytica* can reduce ricinoleic acid to C16, C14, and C12 acids and produce δ-decalactone, a fruity and oily aroma (Sharma et al. 2020). According to Carrau et al. (2005), linalool and citranol produced by *S. cerevisiae* accumulate in wine (Carrau et al. 2005).

FVWs are an important potential substrate for aroma compound production by yeasts. For example, in the study conducted by Guneser et al. (2015), ester and alcohol compounds such as phenyl ethyl alcohol, isoamyl alcohol, isoamyl acetate, phenyl ethyl acetate, and isovaleric acid were produced from tomato and red pepper pulp by *K. marxianus* and *Debaryomyces hansenii*. Furthermore, it was stated that "Tarhana" and "rose"-like flavors were formed in tomato and pepper pulp fermented by *K. marxianus* (Guneser et al. 2015). In addition, it was reported that tomato pulp fermented by *D. hansenii* had the most intense "green bean" flavor. In contrast, pepper pulp fermented by this yeast had "fermented vegetables" and "storage/yeast" flavors (Guneser et al. 2015). In another study, sugarcane pulp was used as waste, and a fruit-like aroma was obtained with the yeast *K. marxianus* (Martínez-Avila et al. 2019). Some aroma components produced by yeasts using FVWs are given in Table 13.4.

5.4 Biofuels

The rapid depletion of fossil fuels and their harmful effects on climate change, sea level rise, biodiversity loss, greenhouse gas emissions that cause urban pollution, and global warming lead to the search for sustainable solutions such as biofuel production for energy production. Biofuels produced in this context are methane, biodiesel, biohydrogen, and bioethanol.

Biodiesel is a mixture of long-chain fatty acids and methyl esters (Chatterjee and Mohan 2018). Although biodiesel is traditionally produced from vegetable oils, waste cooking oils, and animal fats, reducing these raw materials and their economic cost has increased the use of microorganisms that accumulate oil in their cells in biodiesel production. Oleaginous yeast species are an important source of oils used in biodiesel production (Phukan et al. 2019). Some oleaginous yeast species such as *Cryptococcus* sp., *Lipomyces* sp., *Rhodosporidium* sp., and *Rhodotorula* sp. can accumulate intracellular lipids up to 60% of their dry cell weight (Chatterjee and Mohan 2018). Searching for such a match, Chatterjee and Mohan (2018) produced oil with *Cryptococcus curvatus* MTCC 2698 strain using FVWs consisting of waste potato, carrot, cucumber, tomato, brinjal, lady's fingers, cabbage leaves, and pumpkin skins. In another study, in which the yeast, *Cryptococcus* sp., was isolated from a traditional Korean fermented fish and used for bio-oil production, banana peel was used as the substrate. It has been stated that the studied microorganism accumulates up to 34.0% lipid, and this lipid has a high degree of mono-saturation required for quality biodiesel (Han et al. 2019).

FVWs are a good substrate source for ethanol production due to their high carbohydrate content. Rotten sapodilla, papaya, apple, banana, and grapes, pineapple and banana peels, citrus pulp, sugarcane bagasse, and tomato, potato, and cabbage wastes were used for ethanol production (Tiwari et al. 2013; Aruwajoye et al. 2020). In a study by Chitranshi and Kapoor (2021), ethanol production was carried out by *S. cerevisiae* in well-ripe apple, grape, and Indian blueberry fruits (Chitranshi and Kapoor 2021). In another study where *S. cerevisiae* was used for bioethanol production, banana, mango, and grape wastes were used as substrate sources (Shah et al. 2019). Kumar and Senan also used *S. cerevisiae* for bioethanol

Table 13.4 Aroma compounds produced by yeasts by using fruit and vegetable wastes

Fruit/ vegetable waste	Yeast	Aroma compound	Odor	Reference(s)
Sugar beet molasses Sugar beet thick juice Sugar beet sludge	*Aureobasidium pullulans* *Candida lusitaniae* *Meyerozyma caribbica* *Metschnikowia chrysoperlae* *Metschnikowia pulcherrima* *Meyerozyma guilliermondii* *Pichia fermentans* *Pichia kudriavzevii* *Saccharomyces cerevisiae* *Wickerhamomyces anomalus*	2-phenylethanol (2-PE)	Rose	Chreptowicz et al. (2018)
Vinasse + molasses	*Saccharomyces cerevisiae* CCMA 0186 *Saccharomyces cerevisiae* CCMA 0188 *Candida parapsilosis* CCMA 0544 *Candida glabrata* CCMA 0193 *Meyerozyma caribbica* CCMA 0198	2-PE	Rose	Coimbra et al. (2021)
Vinasse	*Wickerhamomyces anomalus* *Candida glabrata* *Candida utilis* *Candida parapsilosis*	2-PE 2-phenylethylacetate (2-PEA)	Flower	Rodríguez-Romero et al. (2020)
Orange peel	*Saccharomyces cerevisiae*	Isoamyl acetate Ethyl decanoate Decanoate Octanoate phenyl Ethyl acetate	Fruity	Mantzouridou et al. (2015)
Orange pulp Potato pulp Molasses	*Saccharomyces cerevisiae* AXAZ-1	2,6-Dimethyl-2-heptanol 1-Octanol Phenylethyl alcohol 2-Hexanone 3-Heptanone 2-Heptanone	Citrus Herbal, toast bread Sweaty, fruity Green Grape	Aggelopoulos et al. (2014)

(continued)

Table 13.4 (continued)

Fruit/ vegetable waste	Yeast	Aroma compound	Odor	Reference(s)
		2-Methyl-4-heptanone Valeric acid	Banana Fruity Sweaty, pungent, cheesy	
		p-Xylene Benzene-1,3,5-trimethyl α-Caryophyllene Valencene Hexamethyleneimine	Cold meat fat Herbaceous, aromatic Oily, fruity, woody Pepper, orange Pepper	
Orange pulp Potato pulp Molasses	*Kluyveromyces marxianus* IMB3	Pentanoic acid-1-methylethyl ester 2,6-Dimethyl-2-heptanol Phenylethyl alcohol 2-Hexanone 3-Heptanone 2-Heptanone 2-Methyl-4-heptanone p-Xylene Benzene-1,3,5-trimethyl α-Caryophyllene Valencene Hexamethyleneimine	Candy, strawberry Citrus Sweaty, fruity Green Grape Banana Fruity Cold meat fat Herbaceous, aromatic Oily, fruity, woody Pepper, orange Pepper	Aggelopoulos et al. (2014)

production and used pineapple, cashew fruit, and banana peel wastes as substrates (Kumar and Senan 2020).

In Table 13.5, the yeasts and FVW used in bioethanol production are given.

6 Future Perspectives and Conclusion

The use of FVWs in various biotechnological processes and the production of value-added bioproducts are becoming increasingly common and contribute to the solution of dwindling soil, water, food, and energy resources. The evaluation of industrial FVWs also reduces operating and production costs while also contributing to solid

Table 13.5 Fruit and vegetable wastes and yeasts used for bioethanol production

Fruit/vegetable wastes	Yeast	Reference(s)
Banana, pineapple, papaya, and mango peels	*Saccharomyces cerevisiae*	Jahid et al. (2018)
Apple, grape, pineapple, pomegranate, orange, carrot, and beetroot pomaces		Venkateswarulu et al. (2015)
Date palm fruit waste		Ahmed et al. (2016)
Manilkara Zapota fruit waste		Sathish Kumar and Sureshkumar (2021)
Apple, banana, papaya, and grape wastes		Janani et al. (Janani et al. 2013)
Potato, onion, eggplant, red apple, pepper, cucumber, orange, pear, rucola, tomato, bean, purslane, green apple, zucchini, carrot, cherry tomato, watermelon, strawberry, mandarin, banana, and lettuce wastes		Keskin-Gundogdu (2020)
Mango, papaya, and banana peels		Mitiku and Hatsa (2020)
Unripe banana peel		Waghmare and Arya (2016)
Date palm waste		Ahmad et al. (2021)
Corn, pumpkin, and carrot wastes		Yesmin et al. (2020)
Carrot pomace		Demiray et al. (2016)
Spoiled pomegranate, banana, and apple		Chaudhari and More (2020)
Banana and mango peels and pulp		Arumugam and Manikandan (2011)
Rotten pineapples		Hossain and Fazliny (2010)
Mango peel		Reddy et al. (2011)
Indian water chestnuts, sweet potato, pineapple, and jackfruit wastes		Gosavi et al. (2017)
Composite vegetable waste, potato, sweet potato, and yam wastes		Chatterjee and Venkata Mohan (2021)
Pineapple, orange, African star apple, tomato, banana, lime, pawpaw, soursop, watermelon, apple, plantain, and almond wastes	*Saccharomyces carlsbergensis*	Ogidi et al. (2020)
Banana, papaya, napa cabbage wastes	*Candida krusei* *Hanseniaspora guilliermondii*	Utama et al. (2019)

(continued)

Table 13.5 (continued)

Fruit/vegetable wastes	Yeast	Reference(s)
Banana, apple, pineapple, mango, and melon wastes	*Wickerhamomyces* sp.	Zanivan et al. (2021)
Carrot pomace	*Kluyveromyces marxianus*	Yu et al. (2013)
Banana peel	*Kluyveromyces marxianus*	Palacios et al. (2017)
Rotten grapes, apple, and sapota	*Candida tropicalis* (mix culture with *Zymomonas mobilis*)	Patle and Lal (2007)
Sugarcane bagasse	*Candida shehatae*	Chandel et al. (2007)
Molasses	*Pichia kudriavzevii* *Kluyveromyces marxianus*	Avchar et al. (2021)

waste management and environmental pollution. The high sugar content of FVWs increases the tendency to use them as substrates in fermentation applications. There are many products with high added value, such as pigments, enzymes, biofuels, and flavorings, which are produced by yeast using FVWs. The most important yeast used in bioproduct production is *S. cerevisiae*. Since *S. cerevisiae* is traditional yeast, it is also widely used in metabolic engineering studies. As mentioned in this chapter, there are still relatively few studies on the production of bioproducts such as enzymes and biogas from yeasts using FVWs, and this area is open to research. The production of bioproducts instead of synthetic products in the world and the use of food wastes such as FVWs for this purpose is promising and requires new industrial breakthroughs.

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Chapter 14
Microbial Production of Polysaccharides, Oligosaccharides, and Sugar Alcohols from Vegetables and Fruit Wastes

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Abstract The use of agricultural wastes and by-products as substrate to produce polysaccharides, oligosaccharides, and sugar alcohols has gained interest in the last few years due to the environmentally friendly approach, the cost reduction in the use of substrate, and the high yields that can be produced using certain microorganisms. Various studies have been carried out to examine how the use of different microorganisms and their enzymes, fermentation and process parameters, such as pH, temperature, C:N ratio, aeration, inoculation size, incubation period and surfactants, can influence the yield and productivity of these compounds. Limiting factors are also considered, and several studies have examined ways of limiting their presence.

Keywords Fruit and vegetable wastes · Microbial polysaccharides · Xanthan · Pullulan · Curdlan · Oligosaccharides · Xylitol · Sorbitol · Mannitol

Abbreviations

CXR	Xylose reductase
DSC	Differential scanning calorimetry
EPSs	Exopolysaccharides
FDA	Food and Drug Administration
FOS	Fructo-oligosaccharides
FT-IR	Fourier-transform infrared spectroscopy

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FVW	Fruit and vegetable wastes
MS	Mass spectrometry
NMR	Nuclear magnetic resonance
OFAT	One factor at a time
POS	Pectooligosaccharides
RFO	Raffinose oligosaccharides
RSM	Response surface methodology
SEM	Scanning electron micrographs
XOS	Xylooligosaccharides

1 Introduction

Fruit and vegetable wastes (FVWs) can be converted into various bio-commodities *via* the use of certain microorganisms. Using the green processes such as the use of FVWs for the production of valuable products is gaining more and more attention as efforts are increasing on limiting the greenhouse gas emissions. Genetic engineering *via* protoplast fusion and recombinant DNA-based processes have been examined for incorporating genes of interest to the microbial genome to produce high yields of high-quality products. Experiments on the use of such wastes for the production of valuable products indicate that the technology has a lot of potential, yet the findings of these studies need to be trialed at commercial scale (Panda et al. 2016). Large quantities of FVWs are produced when agricultural products are processed and usually include nonedible parts of plants such as stems, stalks, leaves, shells, peels, lints, seed/stones, pulp or stubbles, etc. Due to the large amounts of such wastes that are produced yearly, they are one of the most abundant renewable resources on the planet. These wastes contain high amounts of fibers, proteins, and minerals, which are all very important from an industrial perspective (Mussatto et al. 2012). The advantage of FVWs over other types of wastes such as mining spillage, plastic, etc. is that they can act as substrates for growing selected microorganisms that can ferment the material, producing value-added products. Horticultural residues and effluents have been found to contain higher amounts of nutrients such as starch, sugar, phenol, vitamins, and minerals in comparison to other agricultural wastes and have therefore attracted attention in the field of bioprocess engineering (Panda and Ray 2015). These residues can retain large amounts of bioactive compounds such as proteins, carbohydrates, polyphenols, and carotenoids, even after intense processing (Coman et al. 2020).

2 Microbial Polysaccharides

Bacteria can be used to effectively convert carbon and nitrogen sources into various biopolymers including polysaccharides, polyamides, polyesters, polyphosphates, extracellular DNA, proteins, and products thereof, thus being of interest for medical and industrial applications (Moradali and Rehm 2020). The process of generating exopolysaccharides (EPSs) using microorganisms has to a great extent not been explored. Some microorganisms can lead to the production of up to 40 g/L of EPS in relatively simple, yet expensive production operations. Around 30 strains of eukaryotic and prokaryotic microorganisms have been noted to be effective in the production of EPS. The production of EPSs is a result of exposing microorganisms to biotic and abiotic stress or forcing them to adapt to extreme environments. The synthesis of heteropolysaccharides and a number of homopolysaccharides can be carried out by microorganisms, while homopolysaccharides are commonly synthesized outside the cells after certain enzymes are exuded. Even though microorganisms can naturally produce the desired products, physical or chemical extraction techniques are often employed to increase the yield of EPSs (Donot et al. 2012). Microbial polysaccharides can be more expensive than standard polysaccharides and the significant reduction of the cost of these processes is still not possible (Behera and Ray 2016). A number of polysaccharides produced by microorganisms can act as storage compounds. Polysaccharides excreted by the cells are called EPSs and are very important from a marketing perspective. The microbial polysaccharides may have neutral pH (as in the case of dextran and scleroglucan) or be acidic (such as xanthan and gellan). Acidic polysaccharides that have ionized groups can act as polyelectrolytes and are of higher importance for the industry (Bhatia 2016).

The microbial production of polysaccharides, oligosaccharides, and sugar alcohols from vegetables and fruit wastes is given in Table 14.1.

2.1 Xanthan

Xanthan gum can be described as a water-soluble polysaccharide that can be produced using carbon sources such as sucrose, glucose, and wastes of agricultural origin, *via* fermentation using *Xanthomonas campestris*. Xanthan gum has been found to have numerous uses in the food, chemical, personal care, pharmaceutical, and other industries, mainly due to its physicochemical characteristics, which include stable viscosity at broad pH ranges and temperatures and its characteristic pseudoplastic behavior when used at low concentrations. Xanthan gum has been approved by the US Food and Drug Administration (FDA) and is employed as a high-quality stabilizer, thickener, and emulsifier or even food additive, with or without quantitative limitations (Murad et al. 2019). In contrast to all its advantages, xanthan gum's production is very expensive when pure sucrose is used as substrate

Table 14.1 Microbial production of polysaccharides, oligosaccharides, and sugar alcohols from vegetables and fruit wastes

Fruits/vegetable wastes	Microorganisms	Microbial products/ enzymes	Product yield	References
Apple and grape pomace, citrus, potato peel, etc.	*Xanthomonas* spp.	Xanthan gum	2.87–2.9g/ 50g	Vidhyalakshmi et al. (2012)
Green coconut shell, passion fruit peel, straw, and corn cobs	*Xanthomonas campestris* bv. *campestris*	Xanthan gum	1–6.7g/ L	dos Santos et al. (2016)
Passion fruit peel	*X. campestris*	Xanthan gum	8.15–14.81g/ L	Santos et al. (2021)
Peel (waste) of mango and sapodilla	*X. campestris*	Xanthan gum	11.83–20.84g/ L	Chatterji et al. (2015)
Peach pulp	*X. campestris*	Xanthan gum	0.1–0.2 g/L	Papi et al. (1999)
Carrot and pumpkin	*X. campestris*	Xanthan gum	31.4–40.88g/ L	Shiram et al. (2021)
Date syrup	*X. campestris*	Xanthan gum	0.89 g/100 mL	Moosavi-Nasab et al. (2009)
alm juice waste	*X. campestris* NRRL B-1459	Xanthan gum	24.5–43.35g/ L	Salah et al. (2010, 2011a)
Date extract	*X. campestris* PTCC1473	Xanthan gum	–	Khosravi-Darani et al. (2011)
Grape juice concentrate	*X. campestris*	Xanthan gum	0.19 g/L/h⁺	Ghashghaei et al. (2016)
Citrus wastes	*X. campestris*	Xanthan gum		Bilanovic et al. (1994)
Grape skin pulp	*Aureobasidium pullulans*	Pullulan	22.3–30.8 g/L	Israilides et al. (1994)
Carob pod extracts	*A. pullulans*	Pullulan	6.5 g/L	Roukas and Biliaderis (1995)
Jerusalem artichoke	*A. pullulans* and *Kluyveromyces fragilis*	Pullulan	15.5 g/L	Shin et al. (1989)
Hydrolyzed sweet potato	*A. pullulans* AP329	Pullulan	29.43 g/L	Wu et al. (2009)
Hydrolyzed potato starch waste	*A. pullulans* P56	Pullulan	19.2 g/L	Göksungur et al. (2011)
Jerusalem artichoke	*A. pullulans* HA-4D	Pullulan	15.2 g/L	Xia et al. (2017)

(continued)

Table 14.1 (continued)

Fruits/vegetable wastes	Microorganisms	Microbial products/ enzymes	Product yield	References
Cassava bagasse	*A. pullulans* MTCC 1991	Pullulan	27.5 g/kg	Ray and Moorthy (2007)
Date palm juice by-products	*Rhizobium radiobacter* ATCC 6466	Curdlan	22.83 g/L	Salah et al. (2011b)
Agricultural by-products (cassava bagasse, wheat bran, etc.)	*Agrobacterium* species	Curdlan	–	West (2020)
Pineapple waste	–	Fructooligosaccharides (FOS)	150.46 (g/ml)	Dini et al. (2018)
Pine apple (peels, pulps, and leaves)	*Bacillus* sp.	Fructosyltransferase (FTase	0.91 U/ml	Tan et al. (2020)
Ripe plantain peel and kola nut pod	*Aspergillus niger*	β-D-fructofuranosidase (FFase)	20.77–27.77 U/g	Lateef et al. (2012)
Cassava peel and cassava steep liquor	*Rhizopus stolonifer* LAU 07	Fructosyltransferase (FTase)	32.87 U/mL	Lateef and Gueguim-Kana (2012)
Banana peel and leaf	*Chrysonilia sitophila* PSSF84	FFase	21.67–23.4 U/mL	Patil et al. (2011)
Apple pomace	*Aspergillus versicolor*	FFase	–	Arfelli et al. (2016)
Cashew apple juice	*Lactobacillus acidophilus* and *Lacticaseibacil-lus casei*	FOS and raffinose oligosaccharides	–	Kaprasob et al. (2018)
Andes berry (*Rubus glaucus*) and tama-rillo (*Cyphomandra betacea*)	*Aspergillus oryzae* N74	FFase	–	Ruiz et al. (2014)
Orange fruit wastes	–	Xylooligosaccharides	–	Gupta et al. (2017)
Banana peel	*Candida tropicalis* DSM 7524	Xylitol	24.7 g/L	Rehman et al. (2018)
Almond shells	*C. tropicalis* DSM 7524	Xylitol	–	Espinoza-Acosta (2020)
Banana leaves	*C. tropicalis*	Xylitol	8.1 g/ L	Shankar et al. (2020)
Walnut shells	*C. tropicalis* IFO0618	Xylitol	–	Tran et al. (2004)
Extract of Jerusalem artichoke	*Levilactobacill-us brevis* 3-A5	Mannitol	199.86 g/L	Cao et al. (2018)

(continued)

Table 14.1 (continued)

Fruits/vegetable wastes	Microorganisms	Microbial products/ enzymes	Product yield	References
Celery by-products (stalks and leaves)	–	Mannitol	–	Rupérez and Toledano (2003)

for the fermentation, which renders the use of FVW a very attractive alternative (Shiram et al. 2021).

Therefore, the production of xanthan gum from FVW has been studied extensively and results of some of the most important ones being discussed below. In the study of Vidhyalakshmi et al. (2012), an attempt was made to produce xanthan gum from FVWs (i.e., apple and grape pomace, citrus, potato peel, etc.) by different *Xanthomonas* spp. (i.e., *X. campestris*, *X. citri, X. oryzae,* and *X. musacearum*) using solid state fermentation. The process generated a dry weight of 2.9 g xanthan gum/50g of substrate when *Xanthomonas citri* was used as the fermentation microorganism and 2.87 g xanthan gum/50g using *X. campestris* and was therefore noted that the yield was not significantly different when these two microorganisms were used.

The importance of the substrate used for the fermentation was also apparent in the study of dos Santos et al. (2016). In this study, urea (0.01%) and potassium phosphate (0.1%) were added to green coconut shell, passion fruit peel, straw, and corn cobs extracted broth. The pH was brought to 7.0 and the mixture was sterilized at 121 °C for 15 min and then subjected to fermentation for 100 h using *X. campestris* bv. *campestris*. It was observed that more substrate was consumed, and more xanthan gum was generated when green coconut shells (50% and 5.5 g/L) and passion fruit (54.7% and 6.7 g/L) were used in comparison to maize straw (72.6% and 1 g/L) and cob (46.6 and 2.2 g/L)]. Santos et al. (2021) reached to the same conclusion on the importance of the substrate for the production of xanthan gum. In their study, they assessed how different substrates of agricultural origin (cheese whey and passion fruit peel) affected the yield and the rheological properties of the product. It was found that the composition of the substrate significantly affected yield (8.15–14.81 g/L) and apparent viscosity (31.9–510 mPa.s). Other materials could be used though to assist the fermentation and their composition could also affect yield. In the study of Chatterji et al. (2015), mango (*Mangifera indica*) and sapodilla (*Manilkara zapota*) peels were used as substrates for the production of xanthan gum by *X. campestris* and its subsequent use as an agar substitute. The wastes were batch-fermented, and the growth factors of both media were optimized to pH 6.0 and pH 7.4, respectively, at 30°C for 24h. It was found that the product yield (20.84 g/L and 11.83 g/L for mango and sapodilla media, respectively) that was obtained using chilled isopropanol was significantly increased in comparison to the yield (4.8 g/L) obtained using standard media (yeast, glucose, malt, and peptone). In the case of mango, the process was abandoned due to the production of precipitate. The substitution of agar (nutrient agar, luria bertani agar, and sabouraud's agar media) in microbial culture media was achieved using xanthan gum from sapodilla media and combined with agar (1.5% xanthan +0.5% agar and 1% xanthan +0.5% agar). It was found that the new media could effectively support the growth of *Escherichia coli, Bacillus pumilus, Staphylococcus aureus, Saccharomyces cerevisiae,* and *Bacillus cereus*, while it is biocompatible and soluble and has a stable nature, in addition to its production being more environmentally friendly (Chatterji et al. 2015).

High yields of xanthan gum were also obtained in the study of Shiram et al. (2021), in which carrot and pumpkin peels known to contain high levels of glucose, sucrose, vitamins, and minerals were used as substrate for fermentation *by X. campestris*. The effects of pH, whey, and vitamin supplements were all examined. The purification of the xanthan gum was carried out using chilled isopropyl alcohol. The yields of xanthan gum using carrot, pumpkin, and MGYP (Malt extract–Glucose–Yeast extract–Peptone) medium at a pH of 6.0 were 40.88 g/L, 31.4 g/L, and 14.06 g/L, respectively. It is important to note that small pH changes (of less than 1 value) could negatively affect the produced yield to a great extent, while the use of vitamins increased the yield noticeably (Shiram et al. 2021).

In another study, a comparison was made between four different fractions of citrus-derived wastes (whole citrus, pectic, hemicellulosic, cellulosic extracts) as substrates for fermentation, aiming at producing xanthan gum. The waste was a very good candidate for glucose media. *X. campestris* used both simple and complex carbon substances or citrus origin and the consumption of the pectin extract-based substrate was similar to those of whole citrus and pectic extract. It was therefore concluded that water-soluble compounds in citrus waste such as pectins, organic acids, and simple carbohydrates could be easily transformed into xanthan gum but were also the principal contributors to xanthan production from whole citrus waste. Hemicellulose and cellulose extracts were significantly less biodegradable in comparison to pectic extract (Bilanovic et al. 1994).

X. campestris was employed in another study to produce xanthan gum used as substrate date syrup from low-quality fruits. A rotary benmarin shaker (240 rpm) was used for the fermentation of date and sucrose syrup. The process took place at 28 °C and a pH of 6.8. The effect of the fermentation period (24, 48, 72, 96, and 120 h) on the production of xanthan gum was assessed, and it was revealed that the EPS concentration increased by increasing the fermentation time achieving a maximum yield of 0.89 g/100 mL after a period of 96 h. A significantly higher yield was obtained using this medium compared to using a sucrose-based medium (0.18 g/100 mL). With regard to the pH, it was found that the optimum value for obtaining the highest yield was 5.5. It was therefore suggested that date syrup can act as substrate for the production of xanthan gum with very good yield potential (Moosavi-Nasab et al. 2009). *X. campestris* was also the subject of the study of Salah et al. (2010) who used the microorganism to ferment palm juice waste and produce xanthan gum. A response surface methodology (RSM) combined with a Central Composite Orthogonal Design were employed, and three major independent variables (date juice carbon source, nitrogen source, and temperature) were assessed for their combined or individual effects on xanthan gum yield. The conditions that led to the production of the highest yield were 84.68g/L of carbon source and 2.7g/L of nitrogen source at 30.1°C. The yield produced during the experiment under these conditions was 43.35g/L, which was in close agreement with the prediction given by the model (42.96g/L). The maximum value observed for biomass production was 3.35g/L (2.98g/L predicted by the model). The xanthan gum produced was found to contain glucose, glucoronic acid, and mannose. All in all, the date palm juice waste was found to be quite promising as a substrate for the production of less expensive xanthan gum (Salah et al. 2010).

The same team examined whether date juice could be used as a fermentation substrate to produce xanthan gum by *X. campestris* NRRL B-1459. It was shown that this particular strain was very capable of metabolizing date juice. A maximum xanthan gum yield of 24.5 g/L was reached using 60 g/L glucose and 3 g/L ammonium sulfate during batch fermentation with 5% inoculum size at pH 7, 28 °C, in a period of 48 h. High-performance liquid chromatography (HPLC) revealed that the xanthan gum produced was composed of glucose, glucoronic acid, and mannose (Salah et al. 2011a). In a similar study though, when Khosravi-Darani et al. (2011) evaluated the production of xanthan gum from date extract using *X. campestris* PTCC1473 in submerged fermentation, a decrease of cell growth was seen in carbon source levels of up to 50 g/L The highest degree of cell growth and highest xanthan gum yield were reached at 40 g/L concentration of carbon source. The level of nitrogen source did not affect cell growth significantly, but the highest xanthan gum yield was given when 0.2 g/L of nitrogen source was provided. The ratio of carbon to nitrogen concentration significantly affected the production of xanthan gum.

Also, Ghashghaei et al. (2016) assessed whether low-quality grape juice concentrate can be potentially used as an inexpensive carbon source to produce xanthan gum. The Plackett-Burman Design was employed for evaluating a number of factors that have an impact on the level of xanthan gum produced and its viscosity. The levels of carbon and nitrogen, the size of the inoculum, and the agitation rate were all considered major factors and were assessed. RSM was employed for improving broth culture viscosity and xanthan gum concentration. For this purpose, four independent variables, namely, carbon source (30, 40, 50 g/L), ammonium sulfate as nitrogen source (0.5, 1.25, 2 g/L), agitation (150, 200, 250 rpm), and inoculum size (5, 10, 15% v/v), were taken into account. When optimal conditions were achieved, xanthan gum production and viscosity were 14.35 g/L and 1268 cP, respectively, while the average yield of production and productivity of xanthan within 72 h were recorded as 35% and 0.19 g/L/h, respectively. Finally, Papi et al. (1999) used peach pulp as a fermentation substrate for producing xanthan gum. In this study, the wild type of *X. campestris* and a mutant strain of *Zymomonas mobilis* CP4, with tolerance to sucrose concentrations of up to 40% (w/v), were employed, aiming at producing xanthan gum and ethanol, respectively. The growth of both species was satisfactory (2.7 mg/ml and 1.45 mg/ml in the case of *X. campestris* and *Z. mobilis*, respectively) and 0.1–0.2 g/L and 110 g/L of xanthan gum and ethanol, respectively, were produced.

2.2 Pullulan

Pullulan is a water-soluble glucan gum that the fungus *Aureobasidium pullulans* produces under aerobic conditions. It can be described as a repeating copolymer, chemically structured as {→ 6)-α-d-glucopyranosyl-(1 → 4)-α-d-glucopyranosyl-(1 → 4)-α-d-glucopyranosyl-(1 →}n. Pullulan is widely used in a number of fields including food, health care, pharmaceuticals, etc. (Singh et al. 2008). It is a biopolymer that has been part of numerous patented applications. Nevertheless, although commercially produced for more than 25 years, a limited number of applications have been explored in comparison to the full potential of the polysaccharide. This is, to a great extent, because its production is very expensive. In the past few years though, an increased interest has been seen around the use of the substance especially for use in high-value health-promoting and pharmaceutical applications (Leathers 2003). Prajapati et al. (2013) noted that due to not being hazardous, pullulan has been the subject of study for use in numerous applications, such as gene delivery, targeted drug delivery, tissue engineering, etc., and for diagnostic applications, like perfusion, receptor, and lymph node target specific imaging. The linkage of α (1 → 4) and α (1 → 6) that this polysaccharide possesses is responsible for many of its unique characteristics, such as its adhesive properties and its ability to form fibers.

The classification of pullulan-hydrolyzing enzymes can be carried out on the basis of their substrate specificity and hydrolysis derivatives such as pullulanases (type I and II) and pullulan hydrolases (type I, II, and III). The production of pullulanases and pullulan hydrolase type I is also possible using bacteria and archaea. In terms of using bacteria, a number of mesophilic, thermophilic, and hyperthermophilic organisms can be effectively used, while pullulan hydrolase type II and type III specifically require the use of fungi and archaea, respectively. These are multi-domain proteins possessing three conserved catalytic acidic residues of the glycosyl hydrolases. Pullulanases are debranching enzymes, commonly used for starch saccharification to limit the use of glucoamylase (approx. 50 %) and shorten the time required for the reaction to take place. Due to their thermostability, amylopullulanases can be very effective in one-step starch liquefaction and saccharification processes (Kar et al. 2012), replacing amylolytic enzymes such as α-amylase and glucoamylase, thus rendering the process less expensive. They can also be used in the production of resistant starches and as an antistale in bread making (Nisha and Satyanarayana 2016).

Although pullulan finds applications in various industries and fields, its fermentation production is associated with a number of problems, including (i) the generation melanin pigment, (ii) inhibitory effects as a result of high sugar levels in the medium, and (iii) expensive precipitation and recovery processes (Oğuzhan and Yangılar 2013).

Pullulan is produced *via* fermentation by *A. pullulans* in media containing carbon, nitrogen, and various other nutrients. The cost of the nutrients can be high and is a major factor affecting the cost of pullulan. The use of FVW can therefore be a good cheap alternative due to the nutritional content of these wastes as well as the more environmentally friendly process that involves their use (Singh et al. 2019). Israilides et al. (1994) found that pullulan produced *via* fermentation of grape skin pulp extract, starch, olive oil waste, and molasses was of high purity (up to 97.4% w/w), especially when grape waste was used, while use of supplements containing NH_4NO_3 and K_2HPO_4 allowed yields of up to 30.8 g/L to be given. In another study, Roukas and Biliaderis (1995) used carob pod extracts as a substrate for fermentation by *A. pullulans* in order to produce pullulan. The fermentation was carried out in medium containing 25 g/L of sugar at a pH of 6.5, and at 25-30 °C. Up to 6.5 g/L of pullulan was produced, and the total biomass concentration was 6.3 g/L, while a yield of 30% was given with inoculum at 10% (v/v). The production of pullulan was also reported in the study of Wu et al. (2009) who used the same microorganism and hydrolyzed sweet potato to produce substrate for the fermentation. Up to 29.43 g/L of pullulan were produced indicating that sweet potato can be a suitable fermentation substrate for the production of this polysaccharide. Finally, Göksungur et al. (2011) used hydrolyzed potato starch waste as a fermentation substrate for the production of pullulan by *A. pullulans* P56. The waste was liquefied in a packed bed bioreactor, using pullulanase, and Ca-alginate was used to immobilize amyloglucosidase. Yeast extract was found to be the best nitrogen source and a pullulan yield of 19.2 g/L was possible. Ray and Moorthy (2007) demonstrated that the production of pullulan from cassava bagasse was possible using *A. pullulans* MTCC 1991. Pullulan production (27.5g/kg) was reported when bagasse was used as the sole carbon source but supplemented with mineral medium.

2.3 Curdlan

Curdlan is a water-insoluble β-(1,3)-glucan that can be produced by *Agrobacterium* species on media low in nitrogen. This polysaccharide found its first applications in the food industry due to its convenient heat-induced gelling properties. Research conducted in the last few years focused on how curdlan affects innate and adaptive immunity leading to increased uses in biomedicine (Zhan et al. 2012). Curdlan has found applications in food, non-food, and biomedical fields. Certain carbon sources have been found to allow the effective production of curdlan *via* fermentation by bacteria once nitrogen is depleted from the media. pH plays a crucial role in these fermentation processes (West 2020). Laroche and Michaud (2007) noted that in the case of this polysaccharide, there are efficient and cost-effective processes for its extraction and purification.

The gelation of aqueous suspensions of curdlan was examined in the study of Zhang et al. (2002) by taking rheological measurements and using differential scanning calorimetry and low-resolution time-domain H-nuclear magnetic resonance (NMR). A number of curdlan samples of various molecular weights were used to form gels. A process was developed by these researchers based on the results of this and other studies for interpreting such results, taking into account the plasticization and dissolution of dried material on heating, the time required for polysaccharides to anneal, and the trapping of not perfectly formed pseudo-equilibrium states on re-cooling (Zhang et al. 2002). In the study of Gao et al. (2020), genomic information of CGMCC 11546, a mutated strain of *Agrobacterium* sp. ATCC 31749, developed to produce high yield, was employed to study the biological process of curdlan formation. The maximum yield given was 47.97 ± 0.57 g/L and was achieved using media that contained 60 g/L sucrose, 6 g/L yeast, 2 g/L KH_2PO_4, 0.4 g/L $MgSO_4 \cdot 7H_2O$, 2 g/L $CaCO_3$, 0.1 g/L $FeSO_4 \cdot 7H_2O$, 0.04 g/L$MnSO_4$, and 0.02 g/L $ZnCl_2$ at 30 °C and 280 rpm after a fermentation period of 96 h. A 41% strength improvement in the gel was possible by removing the β-1,3-glucanase genes *exoK* and *exsH* of strain CGMCC 11546. Moreover, it was mentioned that the use of such method led to the production of very-high-quality noodles.

Considering its applications, a study was carried out to examine how curdlan affects the color, syneresis, qualitative characteristics during cooking, and texture of potato starch noodle when present at a level of 0–1.0% w/w. The interactions of the polysaccharide with potato starch were studied in potato starch noodles using Fourier-transform infrared spectroscopy and scanning electron micrographs. It was shown that syneresis was significantly increased and cooked weight showed a decrease, while firmness was improved. The tensile strength of the product was increased when curdlan was present at a level of 0.3–1.0%, and lightness (L^* value) and yellowness (b^* value) were increased when curdlan was present at levels of 0.1–0.5 and 1.0%, respectively ($p<0.05$). It was suggested that the effect of curdlan on all these parameters, with the exception of color, could be due to enhanced hydrogen bonding and the tighter structure within the product. Generally, adding curdlan into potato starch noodle could shorten the aging period needed for the production of the product and improve its texture (Wang et al. 2010). Similarly, Cai and Zhang (2017) mentioned that curdlan can be a very interesting polysaccharide for the food industry, acting as a gelling agent or to improve the texture of food, but it can also be important in biomedical applications. Regarding the latter, despite its profound advantages, including gelling formation characteristics, mild processing, being non-digestible or cytotoxic, it is not well dissolved in water and has no specific attachment sites for anchorage-dependent cells. These two factors can therefore limit its potential for use in medicinal applications. Nevertheless, the hydroxyl groups found in each monomer of curdlan can be chemically modified and functionalized allowing an optimization of its physical, chemical, and biological characteristics.

The gel formation properties of curdlan were also examined in the study of Wei et al. (2018). Alaska surimi with 2%, 3%, and 4% of curdlan was subjected to high temperature treatment in this study. Dynamic rheology and differential scanning calorimetry indicated that the polysaccharide rendered the proteins in the gel more stable and allowed gel proteins and actomyosin to interact more easily, because of which proteins were not aggregated or denatured, and the thermal transition temperature increased. Scanning electron microscopy proved that curdlan allowed a more ordered and denser gel to be formed, while the fibrils became more delicate, allowing the surimi to retain more water.

Two important studies that examined the production of this polysaccharide using FVWs were those of Salah et al. (2011b) and West (2020). The study of Salah et al. (2011b) was carried out to examine whether date palm juice waste can be used as a substrate for the production of curdlan production using for the fermentation *Rhizobium radiobacter*. Several factors such as pH, temperature, inoculum ratio, speed of agitation, carbon content, nitrogen, and fermentation time were studied in order to determine the optimum conditions for producing the highest possible yield. It was shown that this bacterium strain was able of using the substrate, giving a yield of 22.83 g/L when optimum fermentation conditions were used (pH 7; ammonium sulfate 2 g/L; date glucose juice, 120 g/L at 30 °C). The best inoculum ratios, speed of agitation, and fermentation time were determined at 5 ml/100 ml, 180 rpm, and 51h, respectively. The curdlan produced had a molecular weight of 180 kDa, beta-(1,3)-glycosidic linkages as the only monomers, a melting temperature of 1.24 °C, and a glass transition temperature of -3.55 °C.

West (2020) discussed the production of curdlan using *Agrobacterium* species for fermenting agricultural coproducts and plant lignocellulosic hydrolysates. Isolation of certain strains (ATCC 31749 and ATCC 31750) generated *via* mutations and selection processes, which were found to give very high yields, was achieved. Among the agricultural coproducts used as fermentation media, cassava starch waste hydrolysate (carbon source) and wheat bran (nitrogen source) were the most effective for the growth of ATCC 31749, with the fermentation being carried out at 30 °C. Prairie cordgrass hydrolysates could also be used to produce curdlan by ATCC 31749, but a strain derived from ATCC 31749 was found that even doubled the yield.

3 Oligosaccharides

Oligosaccharides are produced at an industrial scale using mainly enzymes, although certain oligosaccharides such as soya bean-derived and lactulose require different processes. The use of enzymes offers the advantage that very specific polysaccharides can be produced, which can be regulated based on the enzyme used (Prapulla et al. 2000). One of the reasons why fructo-oligosaccharides (FOS) are of particular interest for the industry and researchers is because they have prebiotic activity. At an industrial scale, the production of FOS is carried out using microbial enzymes from sucrose. As not only prebiotic FOS but also different types of FOS and other saccharides are produced *via* this process, the prebiotic activity of the final mixture is significantly reduced. It is therefore important that FOS product with higher purity is obtained (Nobre et al. 2015). Wastes of agricultural origin, acting as fermentation substrates, can easily be adjusted to produce a certain type of polysaccharides, such as pectooligosaccharides (POS), xylooligosaccharides (XOS), etc. These substances can be prebiotics of high value or be sold as food supplements (Cano et al. 2020).

3.1 FOS

FOS can be described as sweeteners of low calorific value that show prebiotic activity (Dini et al. 2018). They can positively influence several physiological functions and promote well-being. They are found in nature in several fruits and vegetables in trace amounts, but can only be produced at an industrial scale using enzymes of microbial origin and di- or polysaccharides (e.g., sucrose or inulin) as fermentation substrates (Ganaie et al. 2014).

The production of FOS using enzymes from *Ananas comosus* by-products has been reported. *A. comosus*, known as pineapple, is available all over the world, and particularly in Asia. One factor at a time (OFAT) by RSM using Design Expert version 7.0 was employed for maximizing the levels of FOS produced *via* the enzymatic reaction of sucrose with enzymes derived from the fruit. The reaction took place at 30–90 °C, pH 3–9, and lasted for 10–120 min, while the level of sucrose available was 20%–80% w/v. Enzymes (10%–100% w/v) was used. The optimal conditions for the fermentation were determined as 100 min fermentation time, 60°C, pH of 5.5 with sucrose 60% w/v and 30% w/v enzymes. Under these conditions, 150.45 (g/ml) of FOS was produced (Dini et al. 2018). The study of Tan et al. (2020) also presented an experiment, as part of which peels, pulps, and leaves of pineapples were used as substrates for fermentation by five different Gram-positive bacteria belonging to *Bacillus* sp. All bacteria groups were characterized by hydrolytic and fructosyltransferase activity, but bacteria isolated from leaves demonstrated the highest fructosyltransferase activity (0.91 U/ml).

In a different study, five strains of *Lb. acidophilus*, *La. casei*, *Lactoplantibacillus plantarum*, *Leuconostoc mesenteroides*, and *Bifidobacterium longum* were tested for their potential in increasing the levels of B-group vitamins, FOS, and raffinose oligosaccharides (ROS) of cashew apple juice. Even though both *Lb. acidophilus* and *La. casei* increased B-group vitamin contents by 19.25% and 23.11%, respectively, the final vitamin B2 levels were not found to be significantly different. It was also shown that the total levels of fructose, glucose, galactose, sucrose, melibiose, and maltotriose declined during the 48 h of fermentation. *Lb. acidophilus* and *Lp. plantarum* produced the highest raffinose oligosaccharides and FOS yields. It was therefore concluded that cashew apple juice could, following fermentation, provide a suitable prebiotic source, rich in B-group vitamins (Kaprasob et al. 2018).

Finally, the study of Ruiz et al. (2014) assessed whether FOS could be produced using fructosyltransferase generated by *Aspergillus oryzae* N74, using wastes from the dehydration process of Andes berry (*Rubus glaucus*) and tamarillo (*Cyphomandra betacea*). The experiments were run at both experimental and industrial scales, using both concentrated and non-concentrated waste. While the production yield was not significantly different ($p > 0.05$) (31.18%–34.98% for tamarillo and 33.16%–37.52% for Andes berry) when the fermentation was run at an experimental scale, a much higher yield ($58.51 \pm 1.73\%$) was obtained at the industrial scale experiment. In the case of the Andes berry dehydration solution, a yield of

$49.17 \pm 2.82\%$ was given. It was therefore proved that this type of waste can be used as a fermentation substrate for the production of FOS.

3.2 XOS

XOS are part of many functional foods due to their beneficial effects on health. Xylan is one of the most important substances in lignocellulosic materials and is found in abundance in agricultural wastes. As such, it is a very good candidate to be used as a source of XOS. In the industry, the production of XOS is carried out via chemical, enzymatic, or chemo-enzymatic hydrolysis of lignocellulosic components (Li et al. 2012; Jain et al. 2015). The generation of XOS from agricultural wastes has a lot of potential for nutraceutical industries due to the inexpensive and abundant raw materials that can be used as fermentation substrates. The research around this potential is expected to continue due to the health benefits linked to the consumption of XOS, which include, but are not limited to, selective growth stimulation of beneficial gut microflora, reduction of blood glucose and cholesterol, increased mineral absorption from the large intestine, etc. XOS can also be used as sweeteners and have even found applications in preventive medicine (Samanta et al. 2015; Singh et al. 2019).

The action of extracellular xylanase generated by *Streptomyces rameus* L2001 on a number of xylans and XOS was examined in the study of Li et al. (2012). Birchwood xylan and oat-spelt xylan were hydrolyzed using xylanase produced by *S. rameus* L2001, and the principal components given were xylobiose (X2) and xylotriose (X3). Xylanase exhibited almost no activity against X2 and X3, but led to the hydrolysis of xylotetraose (X4) and xylopentaose (X5) which in turn led to the production of X2 and X3 *via* transglycosylation. Based on the fermentation substrate, different levels of reducing sugars were generated by the xylanase (150 mg/g from corncob, 105 mg/g from bean culms, and 133 mg/g from bagasse). When bagasse was used, 2.36, 2.76, 2.03, and 2.17 mg/mL of X2, X3, X4, and X5, were produced, respectively. The structural characteristics of xylobiose and xylotriose produced *via* hydrolysis of corncob xylan were determined using mass spectrometry (MS) and NMR. Also, Gupta et al. (2017) studied the production of XOS using organic wastes (e.g., orange fruit wastes) as substrate for the fermentation. Xylan is abundant in these materials and the wastes could therefore be an environmentally friendly way of producing high-value XOS. As part of the enzymatic process, acetic acid was employed for preparing pellets made of dried orange peels powder, and xylanase was then used to degrade them for 2, 4, 6, and 8 h.

4 Sugar Alcohols

Sugar alcohols are a type of polyols, which can be found at various concentrations in fruits and vegetables, while they are also used by the food industry as sweeteners. Among the most common polyols used in the food industry are sorbitol, mannitol, xylitol, erythritol, etc. Sorbitol, mannitol, xylitol, and erythritol can be produced using microorganisms. The use of microorganisms for producing polyols has been of particular interest lately (Rice et al. 2020). A few important studies involving the use of microorganisms for the production of xylitol and mannitol are discussed below.

4.1 Xylitol ($C_5H_{12}O_5$)

Xylitol is an interesting sweetener that is added in food and pharmaceuticals, as it seems to be promoting some health benefits. Its production is carried out at present at an industrial scale *via* a chemical reduction process requiring high mounts of energy, which renders it very expensive. The use of microorganisms to convert xylitol is promoted as a process friendlier to the environment that can considerably reduce operational costs (Mohamad et al. 2015). Xylitol is a pentahydroxy sugar alcohol that can be found at very low levels in certain fruits and vegetables, such as plums, strawberries, pumpkin, etc. At an industrial scale, its production is mainly based on chemical and biotechnological processes. The part of the chemical production process that principally increases the cost of the total process is purification. Processes using microorganisms and wastes of agricultural origin as substrates both are cost-effective and support the model of circular economy. The production of xylose as a precursor can be carried out using agricultural wastes *via* chemical and enzymatic hydrolysis and the conversion of xylose to xylitol is mainly done using a yeast strain. The hydrolysis is mainly done at low pH levels. Numerous fermentation inhibitor factors are generated during the chemical hydrolysis that are responsible for the reduction of the total xylitol yield, and therefore a process of detoxification is required. The production of xylitol using microorganisms is mainly carried out using *Candida* species, and various factors can influence the effectiveness of the fermentation (pH, temperature conditions, time, availability of nitrogen, and yeast extract level) (Ur-Rehman et al. 2015).

A reaction to produce xylose *via* enzymatic catalysis using autoclaved and non-autoclaved wheat straw was described by Walsh et al. (2018). The reaction was followed by the conversion of xylose to xylitol using a xylose reductase from *Candida guilliermondii*. The treatment of wheat straw was carried out at 40 and 50 °C for a period of up to 9 h at pH 4.5 using different levels of xylanase (12.4 to 37.2 U). The highest xylose yield (9.8%) was given using hydrolyzed autoclaved wheat straw for 3 h with 24.8 U of xylanase (pH 4.5, 50 °C). All in all, the autoclave treatment allowed a reducing sugars yield increase of 22%. The optimal conditions for producing xylitol were a temperature of 30 °C, pH 7 for 8 h with 7.92 U of xylose reductase and 10 mM NADPH with 23.9 g xylose.

In another study, three by-products of agricultural origin containing high levels of xylan (barley bran, corn cobs, and corn leaves) were subjected to hydrolysis using a solution of sulfuric acid, and various treatment conditions were tested for producing xylose solutions that could be used as substrate for fermentation. The hydrolysis conditions were chosen following kinetic models that were built for the generation of xylose, and the levels of reaction by-products that could influence fermentation were also considered. Nutrients were added to the hydrolysates and *Debaryomyces hansenii* was used for the fermentation without including a detoxification step in the process. The inhibition factors most severely affecting xylitol production were present in *Eucalyptus globulus* wood media. On the other hand, media made of hydrolysates of corn cobs, barley bran, and corn leaves allowed an acceptable production (21.2-29 g/L) after 81 h (Cruz et al. 2000).

The biotechnological production of xylitol by *Candida tropicalis* DSM 7524 was investigated (Rehman et al. 2018; Espinoza-Acosta 2020) as an alternative to the chemical approach for converting xylose to xylitol. *C. tropicalis* DSM 7524 was used to convert xylose into xylitol (birch sugar) in solid-state fermentation using banana peels (Rehman et al. 2018) and almond shells (Espinoza-Acosta 2020).

Also, the study of Shankar et al. (2020) was conducted to examine whether banana and water hyacinth leaves could be used to produce xylitol with the simultaneous production of bioethanol. The cellulosic fraction and hemicellulosic sugars from each waste was isolated *via* acid treatment. Fermentation to ethanol of the hydrolysates product of the enzymatic saccharification of the cellulosic fraction of each waste was done by *S. cerevisiae*, while fermentation of the detoxified hemicellulosic sugars to xylitol was done by *C. tropicalis*. The maximum quantities of ethanol produced using enzymatic hydrolysates of water hyacinth and banana leaves were 6.18 and 8.1 g/ L, respectively. The maximum concentration of xylitol was given through using immobilized cells of adapted *C. tropicalis* and detoxified acid hydrolysate of water hyacinth and banana leaves (13.1 and 11.2 g/ L, respectively), and then use of free cells.

Furthermore, in the study of Tran et al. (2004), beech wood and walnut shells were subjected to hydroxylation at 40 °C using enzymes produced by the bacteria *Penicillium* sp. AHT-1 and *Rhizomucor pusillus* HHT-1. The production of 4.1 g of D-xylose was allowed using beech wood and 15.1 g using walnut shells. *C. tropicalis* IFO0618 was used to produce xylitol. A 50% xylitol yield was given using beech wood hydrolyzed solution and 1% yeast extract and glucose.

Finally, hydrolysis of wheat straw and corn cob followed by enzymatic saccharification was used to produce xylose in the study of Ghaffar et al. (2017). Concentration of the hydrolysate was followed by fermentation using *S. cerevisiae* and *Kluyveromyces*. The combined acid hydrolysis and enzymatic hydrolysis allowed a very efficient production of free sugars. The maximum yield that *Kluyveromyces* gave from wheat straw residues and corn cob was 89.807 g/L (volumetric productivity of 0.019 g/L/h) and 87.716 g/L (volumetric productivity 0.018 g/L/h), respectively. It was therefore proved that wheat straw acid and enzyme hydrolyzed wastes could be effectively used to produce xylitol by *S. cerevisiae*.

4.2 Mannitol ($C_6H_{14}O_6$)

Mannitol's chemical formula is 1,2,3,4,5,6-hexanehexol ($C_6H_8(OH)_6$). This polyol is commonly used in the food and pharmaceutical sectors. It is approximately 50% less sweet than sucrose. In nature it is present in marine algae, mushrooms, and tree exudates. It is an isomer of sorbitol and is mainly produced via hydrogenating glucose syrups. It is offered in various types of granules or crystals and is highly soluble in water (Shawkat et al. 2012).

Mannitol was synthesized from celery by-products in the study of Rupérez and Toledano (2003). According to these authors, celery stalks or stalks and leaves together were treated with hot ethanol 85% leading to sugars and mannitol being solubilized. The identification and quantification of low-molecular-weight carbohydrates was done using high-performance liquid chromatography. The two celery by-products used contained quite similar sucrose levels (5.7–5.9%), but the ratios of hexose (glucose and fructose) to mannitol differed significantly. The content of sugar and mannitol was higher in the stalks (45.5% and 15.2%, respectively) in comparison to the stalk plus leaf (33.9% and 13.3%, respectively). Mannitol accounted for 33.5–39.3% of the carbohydrate content in the wastes.

Furthermore, in another study, Jerusalem artichoke tubers were used to produce mannitol using the bacterium *Levilactobacillus brevis* 3-A5. Enzymatic hydrolysates of the crop's extract were used as fermentation substrate, and it was observed that mannitol yield was significantly reduced when the initial level of reducing sugar increased. A continuous fed-batch fermentation was therefore trialed to improve the yield using the same substrate. Mannitol's concentration reached up to 199.86 g/L at the end of the fermentation, but the productivity for the total process flow was just 1.67 g/L/h. An improvement in the productivity was possible by simultaneously using enzymatic saccharification and fermentation with mannitol production reaching to the levels of 176.50 g/L in 28 h, a productivity of 6.30 g/L/h, and a yield of 0.68 g/g total sugar (Cao et al. 2018).

5 Conclusion and Perspectives

FVWs are produced in massive quantities as a result of agricultural activities and food processing. Despite that, only a small part of these wastes is used to produce added-value products. FVWs are rich in moisture; nutrients, including carbohydrates; and fibers, minerals, and vitamins. They can therefore be a source of nutrients for microorganisms that under controlled conditions ferment these materials, producing valuable products. The use of microbial fermentation to produce polysaccharides, oligosaccharides, and sugar alcohols has been gaining increasing attention in the past few decades. The main reasons are cost reduction due to the use of cheaper FVWs rather than other expensive fermentation substrates, a turn towards a greener economy that aims at reducing disposal of wastes and promoting recycling, as well as the efficient production of these value-added products that find applications in a variety of sectors. A variety of FVWs can be used as substrates for the production of polysaccharides, oligosaccharides, and sugar alcohols. The productivity and yield obtained *via* these processes depend on various factors such as the substrate used and any pre-processing it has been subjected to the microbial strains chosen, often mutants, and the fermentation conditions (pH, temperature, duration of fermentation, etc.). Several factors can inhibit or limit the production of polysaccharides, oligosaccharides, and sugar alcohols during these processes, and therefore steps are often taken to limit their influence. Purification steps are also often needed to isolate the product of interest, although the careful selection of microorganisms means that very specific microbial enzymes are produced, ultimately leading to the production of highly pure product. The potential in the field is extensive and future research is expected to cover all relevant aspects, with studies focusing on trialing and determining new FVW substrates from combination of materials, highly productive microorganisms that can generate high yields under conditions requiring limited energy, and the determination of optimal fermentation conditions.

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Chapter 15
Fluorescent Carbon Dots from Vegetable and Fruit Wastes and Their Applications

Mustafa Çeşme, Hasan Eskalen, and Sadiye Kübra Başkaya

Abstract Fluorescent carbon dots (FCDs) is the youngest member of the carbon nanoparticles family, having superior features such as tunable fluorescent properties, low toxicity, good water solubility, chemical stability, economical and straightforward synthesis methods, and easy functionalization. In the context of these properties, carbon quantum dots are thought to be potential candidates to replace conventional toxic and expensive semiconductor quantum dots. The application areas of these extraordinary zero-dimensional carbon particles have been getting increased day by day. They have been most widely used in sensing, bioimaging, photocatalysis, and optoelectronics applications. In this present chapter, the historical development of FCDs has been mentioned, and brief information about FCDs and their advantages was given. After then, synthesis methods of the FCDs were mentioned. Fluorescence carbon dots can be obtained from a variety of different precursors. Among them, vegetables and fruit as a carbon source is the primary concern of the current review. The fluorescent carbon dots obtained from vegetables and fruit and their waste as a carbon source have been briefly discussed. Further, their applications have been reviewed.

Keywords Carbon dots · Vegetable and fruit wastes · Synthesis method · Recycling · Review

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1 Introduction

Carbon is one of the essential elements in nature. Interest in different carbon nanomaterials such as carbon nanotubes, fullerene, carbon nanoflowers, graphene, carbon nano-onions, and carbon nano-diamonds is increasing day by day. Among different carbon nanomaterials, fluorescent carbon dots (FCDs) are among the most shining stars of carbon-based nanomaterials since their discovery in 2004. CDs are commonly known as spherical-like carbon nanomaterials with less than 10 nm diameter and amusing surface functional groups (Guo et al. 2021a, b). Today, different aspects and applications of FCDs have been studied by scientists around the world because of their extraordinary features such as water solubility, extraordinary chemical stability, high biocompatibility, low toxicity, and adjustable luminescence (Çeşme and Eskalen 2020; Eskalen et al. 2020a, b, 2021; Liu et al. 2021). Semiconductor quantum dots (SQDs) are relatively more expensive nanomaterials in terms of manufacturing steps and cost. They are often known as toxic materials, but FCDs have gained traction in the scientific world as a cheaper and environmentally friendly alternative to SQDs with various applications (Essner and Baker 2017). These unique nanoparticles have potential applications in bioimaging, sensing, optoelectronics, catalysis, and drug delivery (Ashrafizadeh et al. 2020).

The produced food waste in the European Union has reached 89 million tons and continues to rise (Kumar et al. 2020). Moreover, the handling of plant food materials also yields a massive volume of by-products that cause ecological problems (Patra et al. 2021). Research continues to overcome these problems and to obtain valuable products from waste. The peels of fruit and vegetable could be utilized to synthesize novel industrial products such as edible films, biochar, microbiological media, and nanoparticle (Kumar et al. 2020). Although fluorescent CDs might be synthesized using different methods with plenty of other precursors, synthesis methods with lower energy requirements and the use of natural precursors that are easy to obtain stand out one step further in terms of sustainability compared to other synthesis method precursors. Generally, precursors are divided into two parts: first, a variety of natural products, and second, synthetic organic compounds (Yan et al. 2018). The former is used to get low-cost, nontoxic, and sustainable carbon sources. It is a straightforward and unique method to get treasure from vegetable and fruit waste. In the present review, we briefly highlighted the synthesis methods of FCDs. Then, FCDs from vegetable and fruit wastes and their applications were discussed.

2 Synthesis and Characterization Methods of Carbon Quantum Dots

The synthesis and characterization methods of carbon quantum dots are described.

2.1 Synthesis Methods

Carbon dots were incidentally discovered by Xu et al. in 2004 during the separation and purification of single-walled carbon nanotubes (SWCNTs) using gel electrophoresis (Xu et al. 2004; Hill and Galan 2017; Mishra et al. 2018). With this development, a new class of nanomaterials emerged and prompted further studies to take advantage of the fluorescent properties of CDs. Later, various procedures and methods were created for the synthesis of CDs. Generally, CD synthesis methods can be classified into two separate groups: "top-down" and "bottom-up" methodologies. Figure 15.1 shows a schematic depiction of the synthetic methods for CDs.

Under relatively harsh conditions such as oxidative acid treatment, electrochemical exfoliation, laser ablation, and arc discharge, the breakdown of bulk carbon materials into nano-sized carbon occurs in the "top-down" method. FCDs were created using a top-down process that involved laser ablation of graphite in the gas phase followed by oxidative acid treatment for the first time. Later, numerous methods for obtaining CDs by reducing the size of bulk carbon materials were developed, including arc discharge, etching, electrochemical oxidation, ultrasonication, chemical exfoliation, and nitric acid/sulfuric acid oxidation. The lead materials in these methods are mainly carbon fibers, fullerene, graphene or graphene oxide (GO) plates, carbon nanotubes (CNTs), and graphite (Hill and Galan 2017; Peng et al. 2017; Kang et al. 2020).

CDs are made from small carbon-containing molecules in a "polymerization-carbonization" phase in the "bottom-up" approach. Bottom-up synthesis uses numerous approaches, including combustion, hydrothermal, solvothermal, and microwave-assisted pyrolysis. Carbon precursors, such as small organic molecules taken in a liquid or gas phase, are ionized, decomposed, sublimated, or evaporated in

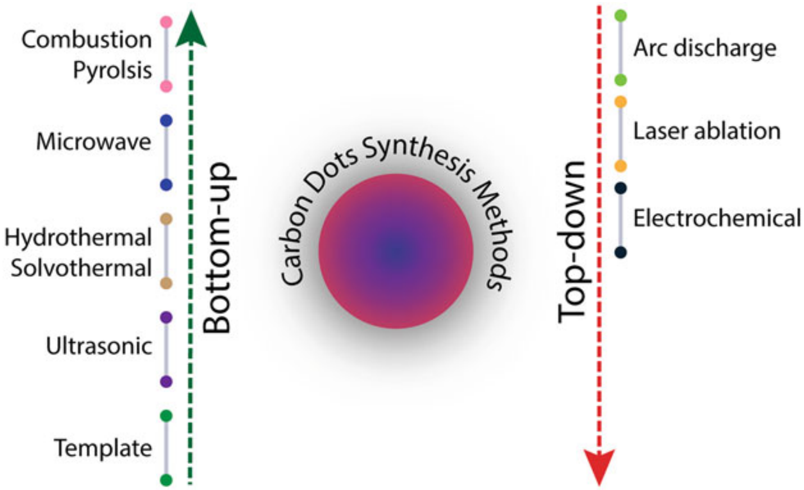

Fig. 15.1 Schematic depiction of the synthetic methods for CDs

these processes, and then nano-sized CDs are generated. Condensation, carbonization, polymerization, and passivation densify them to forms. The "bottom-up" technique is commonly used for the green synthesis of CDs using natural renewable resources, as opposed to the "top-down" strategy (Lim et al. 2015; Hill and Galan 2017; Li et al. 2017; Peng et al. 2017; Kang et al. 2020).

2.2 Characterization

Essential features such as surface functionality, solubility, size, shape, and structure are the most critical characteristic points that determine the unique properties of CDs together with their optical properties. With these key points in mind, many recent efforts have been made to introduce sensitive, high-accuracy, and analytical and instrumental characterization methods for CDs. In this section, analysis techniques required for basic structure identification and clarification in characterizing FCDs are discussed. Schematic depiction of all characterization techniques for CDs is shown in Fig. 15.2.

Various imaging techniques are used for the morphological properties, shape information, structure, and size analysis of nanomaterials. Among the most commonly used microscopic techniques in determining and analyzing the size of nanoparticles, transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM) come to the fore (Zhou et al. 2012; Ahmadian-Fard-Fini et al. 2018). Both SEM and TEM are practical electron microscopy techniques that provide information on the particle size, size distribution, and morphology of CDs. SEM and TEM images can be used to investigate the quality of the distribution of particles and whether or not an agglomeration of particles is present. SEM generates images by scanning the surface of a CD sample with a focused electron beam that interacts with the atoms of the CDs, where charges accumulate to form an image. TEM devices have higher magnification rates as they offer images based on more sensitivity than SEM devices.

The AFM technique is an analytical microscopy procedure used to reveal the morphological features of CDs with a resolution less than 1 nm in size. It produces two-dimensional images compared to other electron microscopy and provides

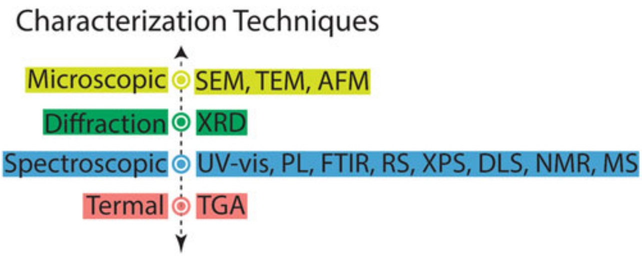

Fig. 15.2 Schematic depiction of all characterization techniques for CDs

three-dimensional details along with the diameters of CDs (Dong et al. 2014; Ghosal and Ghosh 2019; Li et al. 2020).

When X-rays interact with a sample of CDs, an angle-dependent pattern is obtained depending on whether the rays reflected from the sample are constructive or refractive. It provides information about the composition of the obtained pattern CDs (Atchudan et al. 2017; Joseph et al. 2020).

Several spectroscopic techniques were defined for the characterization of CDs, including dynamic light disperse (DLS), UV-Visible (UV-Vis), photoluminescence (PL), Fourier transform infrared spectroscopy (FTIR), and nuclear magnetic resonance (NMR) spectroscopy (Zhao et al. 2015; Park et al. 2019; Wang et al. 2019). DLS technique is used in liquid phase analytical systems equipped with detectors to measure the hydrodynamic particle size of carbon dots (Sorinezami et al. 2019). The average CD diameter could be quantified by measuring the diffusion velocity of C-dotted liquids with this instrument; however, a few typical examples of using DLS determine particle size CDs in the literature (Mehta et al. 2014, 2015). Spectroscopic techniques for measuring the optical properties of CDs are standard and widely available, used for spectroscopy of the UV and PL. All CDs types are active in the UV region of the electromagnetic spectrum combined with UV-Vis and PL spectroscopy, and lambda λ_{ex}-dependent behavior conducts the fluorescent emission of CDs (Hu et al. 2017). IR is a broadly utilized tool for determining the functionalities of compounds. When IR analysis of CD samples is conducted, IR can examine the doping of heteroatoms into the FCDs structure in addition to the assessment of functional groups such as hydroxyl (-OH) and carbonyl (C=O) functional groups on the FCDs surface. Raman spectroscopy is a nondestructive and noninvasive spectroscopic tool that can be used to determine the carbon state of a CD sample (Liang et al. 2020; Tang et al. 2020). CDs have two basic first-order bands in their Raman spectra. The D-band exemplifies the vibrations of carbon atoms with overhanging bonds in the termination plane of irregular graphite or glassy carbon. In contrast, the graphitic band (G-band) represents the vibrations of carbon atoms with overhanging bonds in the termination plane of irregular graphite or glassy carbon. The vibration of sp^2 bonded carbon atoms in a 2D hexagonal lattice is related to the G-band (graphitic band).

NMR spectroscopic method has also been used to obtain more characteristic information about the structure of CDs (Li et al. 2017, 2020; Tang et al. 2020). The principal application of NMR for the illumination of CD characterization aims to precisely define the surface functionality of C points as well as determine the states of elements such as C, N, and P in CDs and study their nature (Mishra et al. 2018; Liu et al. 2019a, b; Park et al. 2020). Mass spectrometry (MS) has been described to be strongly useful in illuminating characterization. Mass spectrometric techniques utilized to characterize CDs include MALDI-TOF MS (matrix-assisted laser desorption/ionization time-of-flight mass spectrometry), ICP-MS (inductively coupled plasma mass spectrometry), and ESI-QTF/MS (electrospray ionization quadrupole time-of-flight sequential mass spectrometry) (Gaddam et al. 2014; Zhao et al. 2019; Ghanem et al. 2020).

DLS technique is used to determine the hydrodynamic particle size. In addition, the diffusion rate of FCDs in liquids can be used to calculate the mean CD radius. Although there are a few famous specimens of using DLS to determine the particle size of FCDs, DLS for characterization of CDs is not commonly used (Hu et al. 2017).

Thermogravimetric analysis (TGA) is the method employed to determine and describe the thermal behavior of CDs. The device constantly weighs an FCDs sample in TGA measurement, combining it with FTIR or MS for gas analysis. A mass loss curve is plotted by measuring the amount of weight loss and rate of change of a CD sample relative to temperature, and information on the thermal stability of the FCDs is provided (Mewada et al. 2014; Chu et al. 2020; Sato et al. 2019).

3 Vegetable and Fruit and Their Waste as Precursors of CDs

Carbon quantum dots have attracted significant attention in recent years due to their excellent physical, chemical, and optical properties. There are various carbon precursors for carbon quantum dot synthesis that find application in many areas, such as food waste, by-products from plants, animal feed, and compounds used in food processing. Among all carbon sources, natural foods and food wastes are advantageous in terms of safety and biocompatibility and have easy synthesis conditions. Synthesizing carbon quantum dots with natural materials without any chemical involvement is essential for avoiding toxicity (Fan et al. 2020).

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Currently, food losses and food wastes are a severe problem worldwide. About a third of the world's food is lost or wasted every year (Xue et al. 2017). The use of food as waste offers economic benefits. The use of food waste with enough carbon sources in carbon quantum dot technology is also advantageous in terms of safety and biocompatibility. Fruit and vegetable wastes contain high amounts of phytochemical components (Galanakis 2012). Some phytochemicals and crucial nutrients are observed in the seeds, peels, and other ingredients of commonly used fruits and vegetables. Proper use of fruit and vegetable wastes will reveal health-promoting approaches while also resolving environmental problems (Rudra et al. 2015). Table 15.1 summarizes the carbon quantum dots, synthesis methods, quantum yields, and areas of use obtained from natural sources such as fruits and vegetables and their various wastes. The synthesis of FCDs from natural resources (fruits, vegetables) and their wastes has advantages such as being obtained by effortless methods, having low cost, environmentally friendly, and readily available from nature.

Table 15.1 The synthetic methods of CDs from various precursors relevant to different applications

Precursors	Methods	QY (%)	Application	Ref.
Mango peel	Pyrolysis	8.5	Fe^{+2} ion detection, cellular labeling	Jiao et al. (2019)
Watermelon peel	Pyrolysis	7.1	Cell imaging	Zhou et al. (2012)
Pomelo peel	Hydrothermal	6.9	Hg^{+2} ion detection	Lu et al. (2012)
Lemon peel	Hydrothermal	14	Cr^{+2} ion detection, photocatalysis	Tyagi et al. (2016)
Onion waste	Hydrothermal	28	Fe^{+3} ion detection, bioimaging	Bandi et al. (2016)
Banana peel	Hydrothermal	20	In vivo bioimaging	Atchudan et al. (2021)
Orange peel	Hydrothermal	36	Photocatalysis	Prasannan and Imae (2013)
Potato peel	Hydrothermal	54	MIP-coated CD fluorescent probe	Liu, H. et al. (Liu et al. 2019a, b)
Passion fruit shell	Hydrothermal	1.8	–	Yang et al. (2020)
Citrus fruit peel	Sand bath (heat-assisted)	–	Cell imaging	Gudimella et al. (2021)
Kiwi peel	Ultrasonication	–	Hg^{+2} ion detection, Cu^{+2} ion detection, cell imaging	Sun et al. (2021)
Carica papaya peel	Pyrolysis	23.7	Cr(III), Cr(VI) ion detection	D'Souza. et al. (2018)
Pineapple peel	Hydrothermal	42	Electronic security device, Hg^{2+} ion detection	Vandarkuzhali et al. (2018)
Strawberry juice	Hydrothermal	6.88	Hg^{2+} ion detection	Huang et al. (2013)
Sweet pepper	Hydrothermal	19.3	CIO^{-} ion detection	Yin et al. (2013)
Mangosteen peel	Pyrolysis	–	–	Aji et al. (2017)
Date kernel	Hydrothermal	12.5	Cellular imaging	Amin et al. (2018)
White pepper	Solvothermal	10.4	Coenzyme A detection imaging	Long et al. (2020)
Vigna radiata	Hydrothermal	58	Fe^{+3} ion detection, cell imaging	Kaur et al. (2019)
Carrot juice	Hydrothermal	5.16	In vitro cellular imaging	Liu et al. (2017)
Winter melon	Hydrothermal	7.51	Bioimaging	Feng et al. (2015)
Cabbage	Hydrothermal	16.5	Bioimaging	Alam et al. (2015)
Dragon fruit	Hydrothermal	–	Bioimaging	Meng et al. (2019)
Yellow cucumber-pineapple peel	Refluxing process	–	–	Himaja et al. (2014)
Saccharum officinarum juice	Hydrothermal	5.76	Fluorescent imaging	Mehta et al. (2014)

(continued)

Table 15.1 (continued)

Precursors	Methods	QY (%)	Application	Ref.
Apple juice	Hydrothermal	4.27	Mycobacterium fungal cell imaging	Mehta et al. (2015)
Ginger juice	Hydrothermal	13.4	Cell imaging	Li et al. (2014)
Orange peel	Microwave	16.2	Detection of *Escherichia coli* in milk	Hu et al. (2021)
Broccoli	Hydrothermal	–	Ag^{+} ion detection	Arumugam and Kim (2018)
Wheat straw, bamboo residues	Hydrothermal	13	Cell imaging, in vivo bioimaging	Huang et al. (2019)
Carrot roots	Hydrothermal	7.6	Drug delivery system	D'souza et al. (2018)
Cherry tomato	Hydrothermal	9.7	Detection of trifluralin herbicide	Lai et al. (2020)
Campomanesia phaea	Hydrothermal	21.3	Zn^{+2} ion detection	da Silva Júnior et al. (2021)
Quince fruit	Microwave	8.55	Cell imaging, detection of As^{+3} ions	Ramezani et al. (2018)
Cranberry beans	Hydrothermal	10.85	Fe^{+3} ion detection	Zulfajri et al. (2019)
Ginkgo fruit	Hydrothermal	3.33	Cell imaging	Li et al. (2017a, b)
Red pitaya peels	Solvothermal	2.4	Au^{+3} ion detection, cell imaging, antioxidant activity	Guo et al. (2021a, b)
Grape peel	Hydrothermal	3.1	Fe^{+3} ion detection	Xu et al. (2015)
Garlic	Microwave	5	Cell imaging, efficient antioxidative	Yang et al. (2015)
Rosemary leaves	Hydrothermal	–	Food storage capacity, fingerprint detection	Eskalen et al. (2020a, b)
Peanut shell	Pyrolysis	10.58	Cu^{+2} ion detection	Ma et al. (2017)
Jujube	Hydrothermal	–	Fe^{+3} ion detection	Kim and Kim (2018)
Pakchoi juice	Hydrothermal	37.5	Cell imaging, Cu^{+2} ion detection	Niu et al. (2015)
Punica granatum juice	Hydrothermal	7.6	Cell imaging	Kasibabu et al. (2015)
Tomato	Chemical oxidation	12.7	Fe^{+3} ion detection, bioimaging	Kailasa et al. (2019)
Beetroot	Hydrothermal-acid treat.	6	In vivo imaging	Singh et al. (2018)
Spinach	Solvothermal	15.34	Bioimaging	Li et al. (2017a)
Indian gooseberry	Hydrothermal	13.5	Bioimaging, fluorescent ink	Atchudan et al. (2018)
Soya bean	Pyrolysis	–	In vitro imaging	Li et al. (2013)
Water chestnut	Pyrolysis	12.6	Bioimaging	Zhan et al. (2017)

QY quantum yields

3.1 Fruit and Vegetable Wastes

Some fruit and vegetable wastes used as carbon sources in the synthesis of fluorescent carbon quantum dots are as follows: mango peel (Jiao et al. 2019), watermelon peel (Zhou et al. 2012), pomelo peel (Lu et al. 2012), lemon peel (Tyagi et al. 2016), onion waste (Bandi et al. 2016), banana peel (Atchudan et al. 2021), orange peel (Prasannan and Imae 2013), potato peel (Liu H. et al. 2019a, b), passion fruit shell (Yang et al. 2020), citrus fruit peel (Gudimella et al. 2021), kiwi peel (Sun et al. 2021), Carica papaya peel (Singh et al. 2019), pineapple peel (Vandarkuzhali et al. 2018), mangosteen peel (Aji et al. 2017), date kernel (Amin et al. 2018), orange peel (Hu et al. 2021), red pitaya peels (Guo et al. 2021a, b), grape peel (Xu et al. 2015), and peanut shell (Ma et al. 2017) (Table 15.1). For instance, the fluorescence quantum yield of carbon quantum dots synthesized by the hydrothermal method at 200 ° C and 10 hr. using mango peel was found to be 0.6%. The carbon quantum dot was synthesized for the second time by employing mango peels, pyrolyzed at 300 ° C for 2 hr. The fluorescence quantum yield was found to be 4.1%. In the third method, after the mango peels are dried and then powdered, they were directly oxidized with H_2SO_4, and the quantum yield was found to be 0.2%. In the fourth method, the second and third methods were combined, and the highest quantum yield was found to be 8.5%. The synthesized carbon quantum dots showed the feature of sensors in the Fe^{+2} ion, and it was also found to have potential in the field of bioimaging (Jiao et al. 2019). Carbon quantum dot synthesis was carried out by pyrolysis method using watermelon peel. The fluorescence quantum yield was found to be 7.1%, and the synthesized carbon dots were successfully applied in the cell imaging field (Zhou et al. 2012). Carbon dots synthesized by the hydrothermal method using pomelo shell have a quantum yield of approximately 6.9%. It was used as a probe for the detection of Hg^{+2} ion (Lu et al. 2012).

3.1.1 Fruits

Fruits were used as a carbon source in the synthesis of carbon quantum dots. Some of these fruits used are as follows: strawberry juice (Huang et al. 2013), carrot juice (Liu et al. 2017), winter melon (Feng et al. 2015), dragon fruit (Meng et al. 2019), sugarcane juice (Mehta et al. 2014), apple juice (Mehta et al. 2015), ginger juice (Li et al. 2014), ginkgo fruit (Li et al. 2017a), quince fruit (Ramezani et al. 2018), pakchoi juice (Niu et al. 2015), *Punica granatum* juice (Kasibabu et al. 2015), jujube juice (Kim and Kim 2018), *Campomanesia phaea* juice (da Silva Júnior et al. 2021), and Indian gooseberry (Atchudan et al. 2018). Nitrogen-doped carbon dots synthesized by one-pot hydrothermal method at 180 °C and 12 hr. using strawberry juice have a quantum yield of 6.8% and have a maximum emission of 427 nm. These synthesized carbon dots were used in the determination of the Hg^{+2} ion (Huang et al. 2013). The quantum yield of carbon dots synthesized at 160 °C and 6 hr. by hydrothermal method using carrot juice is 5.16% and can be applied in the in vitro imaging field. (Liu et al. 2017). In another study, particle sizes and morphologies of carbon dots synthesized by microwave-assisted method and then hydrothermal method using ginkgo fruits were compared. It has been observed that the morphologies of carbon dots synthesized by the hydrothermal method are more homogeneous and have better fluorescence emission characteristics. FCDs produced by the hydrothermal technique were employed in cell imaging utilizing HeLa and KYSE410 cells (Li et al. 2017).

3.1.2 Vegetables

Vegetables used as precursor production of FCDs are as follows: cabbage (Alam et al. 2015), yellow cucumber and pineapple peel (Himaja et al. 2014), sweet pepper (Yin et al. 2013), white pepper (Long et al. 2020), green gram (*Vigna radiata*) (Kaur et al. 2019), broccoli (Arumugam and Kim 2018), wheat straw (bamboo residues) (Huang et al. 2019), carrot roots (D'souza et al. 2018), cherry tomato (Lai et al. 2020), cranberry beans (Zulfajri et al. 2019), garlic (Yang et al. 2015), rosemary leaves (Eskalen et al. 2020a), tomato (Kailasa et al. 2019), beetroot (Singh et al. 2018), spinach (Li et al. 2017b), soya bean (Li W. et al. 2013), and water chestnut (Zhan et al. 2017). For example, the quantum yield of carbon quantum dots synthesized by the hydrothermal method at 140 °C and 5 hr. using cabbage was 16.5%. CQD showed low toxicity to the non-tumorigenic human keratinocyte cell HaCaT cell, and this result is promising for biomedical applications (Alam et al. 2015). The quantum yield of carbon dots synthesized by hydrothermal method at 180 °C and 24 hr. using green gram seeds and ethylenediamine was found to be 58%. These synthesized carbon dots were used as a multicolor fluorescent agent in the detection of Fe^{+3} ions and in cell imaging (Kaur et al. 2019). Carbon dots synthesized by hydrothermal method at 190 °C and 6 hr. using broccoli were used as probes for the determination of Ag^{+} ions (Arumugam and Kim 2018).

4 Applications

Synthesized carbon quantum dots have potential applications in the following areas: bioimaging, chemical sensing (ion detection), photocatalysis, and drug delivery system.

4.1 Chemical Sensing

Increasing heavy metal pollution, which poses serious health risks, is of great concern. Because of this, precise and robust detection of heavy metals is crucial in terms of today's living conditions. Carbon quantum dots used as fluorescent probes or biological sensors are used to detect heavy metals. Table 15.1 contains examples of how some carbon quantum dots synthesized from various fruits, vegetables, and their wastes are used to detect heavy metals. Mercury ions (Hg^{+2}) cause environmental and health problems. They also cause CQD fluorescence quenching by interacting with some groups on the CQD surface (Venkateswarlu et al. 2018). The carbon quantum dots synthesized by the hydrothermal method in a study using pomelo peel as a carbon source were used to determine the Hg^{+2} ion (Lu et al. 2012). CQD synthesized from lemon peel by the hydrothermal method was used to determine Cr^{+2} ion (Tyagi et al. 2016). CQD synthesized from onion peel was used to determine Fe^{+3} ion (Bandi et al. 2016). CQD synthesized from kiwi peel was applied as a fluorescent probe to detect heavy metal ions like Hg^{+2} and Cu^{+2} ions (Sun et al. 2021).

4.2 Bioimaging

The high biocompatibility of carbon quantum dots has shown that they may be applied in biomedical fields. Their nano-size and structural properties have enabled them to be used as agents in in vitro and in vivo imaging. The excellent photostability and good water solubility have increased their applicability in these areas. FCDs were synthesized from watermelon peels by pyrolysis for optical imaging of Hela cells (Zhou et al. 2012). CQD synthesized from banana peel was used as a probe for multicolor imaging of nematodes (Atchudan et al. 2021). FCDs manufactured from citrus fruit peel by a sand bath (heat-assisted method) were significant biological labels of multiple excitations when modified with folic acid (Gudimella et al. 2021). FCDs synthesized by the hydrothermal method using the date kernel was used as a fluorescent probe for sensitive analysis of Zoledronic acid drug in human serum and applied to bioimaging human osteosarcoma MG-63 cell (Amin et al. 2018). FCDs derived from Indian gooseberry juice have been utilized as promising staining agents on HCT-116 human colon cancer cells and *Caenorhabditis elegans* (nematodes) for multicolor cellular imaging. It was also used as fluorescent ink for writing and drawing by anticoagulation (Atchudan et al. 2018).

4.3 Drug Delivery

Carbon quantum dots have been used as a carrier in drug release systems because of their high biocompatibility, large surface areas, and nano-size. For example, fluorescent carbon dots synthesized using carrot roots by the hydrothermal method, an environmentally friendly and one-step method, were used as nanocarriers to release mitomycin. Mitomycin-loaded CD nanocarriers have been shown to enter cells efficiently (D'souza et al. 2018). In another study, multicolored FCDs were produced by microwave irradiation using quince fruit powder. The cytotoxicity of these nanoparticles was investigated with the MTT test. The IC 50% value for HT-29 cells was found to be 924.25 μg/mL, which was nontoxic at concentrations lower than this value. These results show that the synthesized carbon quantum dots can be utilized in cell imaging and drug release systems (Ramezani et al. 2018).

4.4 *Photocatalysis*

Carbon quantum dots have also been used in the field of photocatalysis due to their high chemical stability. A composite was formed using ZnO and CQD synthesized from orange peel using a one-pot and straightforward hydrothermal carbonization technique and was used as a photocatalyst for the degradation of azo dye, which showed promising results (Prasannan and Imae 2013). Blue emission carbon dots synthesized by hydrothermal method using pineapple peel were applied to determine the Hg^{+2} ion in water. It also designed individual basic logic operations such as NOT and IMP gates using CD as probe and Hg^{+2} and L-Cys (L-cysteine) as chemical inputs. The availability of this system in electronic security devices and as a memory element has also been shown (Vandarkuzhali et al. 2018). FCDs synthesized from lemon peel by hydrothermal method exhibited a quantum yield of 14%. These carbon quantum dots obtained have shown photocatalytic activity for the TiO_2-CQD composite and were used to determine Cr^{+6} in water treatment processes (Tyagi et al. 2016).

4.5 *Antioxidant Activity*

While many nanomaterials are known to give oxidative stress to biological systems, carbon dots have free radical scavenging activity in contrast (Das et al. 2014). The carbon dots obtained from solvothermal treatment of red pitaya peels with acetic acid were used to detect and image Au^{+3} ions. It showed high antioxidant activity (Guo et al. 2021a, b). In another study, kiwi peel phenolic extract obtained by ultrasonically assisted extraction technology showed gradient fluorescence properties with solvent effect. The phenolic extract has been found to enhance the antioxidant activity of gelatin-based films. It has been shown that it can also be applied in other areas as a natural antioxidant (Sun et al. 2021). In other study, fluorescent carbon dots obtained from rosemary leaves were found to be carbon sources with antioxidant capability in fruit preservation (Eskalen et al. 2020b).

5 Conclusion and Future Perspectives

In this review, the detailed synthesis methods and fundamental characterization techniques of FCDs were discussed. After then, the literature related to vegetables and fruits and their wastes as FCDs precursors was discussed in depth. The effect of using vegetable and fruit wastes as a carbon source in the production of FCDs in a simple and easy way has made an advance. The quantum yields of FCDs obtained from vegetables, fruits, and their wastes were investigated. Considering the studies examined in this work, it is seen that the hydrothermal method is used more widely than other methods to produce FCDs. Finally, the broad application potentials of FCDs, including chemical detection, bioimaging, drug delivery, photocatalysis, and antioxidant activity, were briefly explored.

Conflicts of Interest The authors declare no conflict of interest.

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Chapter 16
Biocomposites from Fruit and Vegetable Wastes and Their Applications

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Abstract A considerable amount of food waste is generated with increased food production. A sustainable approach is needed to manage this waste generation for the proper valorization and value addition of food wastes. The fruits and vegetables processing sector generates a large amount of waste, approximately more than 42% of total food wastes. Fruits and vegetable wastes are an ideal substrate for the production of biocomposites. These fruits and vegetable wastes can be utilized as sustainable raw materials to produce biocomposites using green technology that is economical, sustainable, and environment friendly. This chapter focuses on synthesizing biocomposites using fruit and vegetable wastes, their application, and environmental sustainability.

Keywords Fruit and vegetable wastes · Waste valorization · Biocomposites · Sustainable approach · Food wastage footprint · Fruit and vegetable waste · Based biocomposites · Eco-friendly biocomposites

1 Introduction

Due to an accelerating population increase and occasional imbalances in supply of food chains, a growing concern has generated increased food waste globally (Ganesh et al. 2021). The Food and Agriculture Organization (FAO) of the United Nations estimates that 793 million people still go hungry worldwide. According to Eurostat, approximately 9.6% of the European population is incapable of a proper meal (with meat, fish, chicken, or a vegetarian equivalent) every other day (FAO 2013). Approximately 1.3 billion tons of food are wasted globally. About 20% of food

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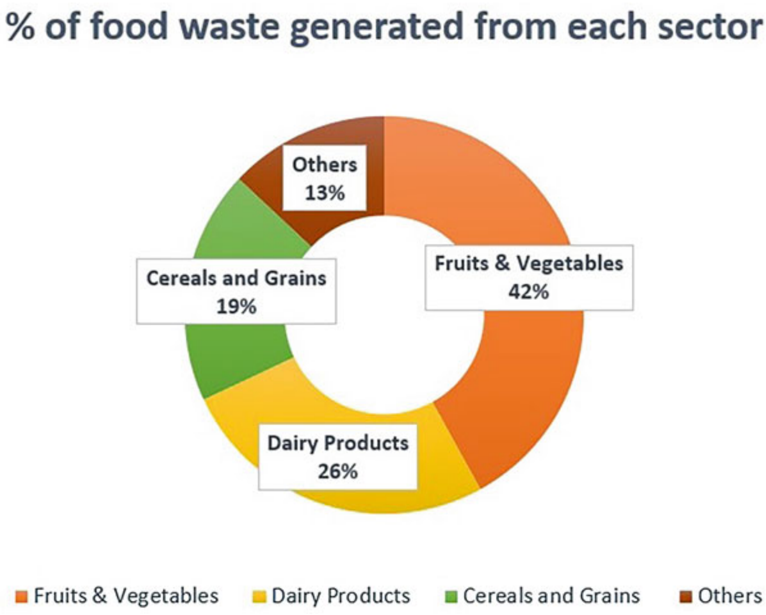

Fig. 16.1 Percentage of food waste generated from each food sector

waste is from production waste, 1% processing waste, 19% waste during supply, and 60% from consumers (Ganesh et al. 2021). Filimonau and Delysia (2019) reported that the survey data of more than 50% of food waste in Scandinavia was due to a challenge in deciding between "best before" and "use by" dates. There are reports concerning the possibility of using waste for value-added foods and proteins to overcome the problem of food immunity with great attention to safety (Umesh et al. 2019; Hashempour-Baltork et al. 2020).

Figure 16.1 shows the percentage of food waste generated from each food sector. Fruit and vegetable wastes (FVWs) account for 42% of the waste produced among the various food materials wasted (Ganesh et al. 2021). These wastes are naturally dumped in landfills, as it is relatively low cost to produce methane as the primary product. Although methane could generate fuel, greenhouse gases (GHGs) have a 25-fold more global warming potential than CO_2 (Ganesh et al. 2021). The FVWs are generated in different forms, as shown in Fig. 16.2.

The effective valorization of waste products in various applications provides a valuable source for reducing environmental issues in a sustainable manner. Given the expanding surge in FVW generation, this chapter aims to review the synthesis of biocomposites from FVWs. First, a brief overview of food wastage and climate change from FVWs is provided. Preparation methods like injection molding, compression molding, film formation, and improvement in mechanical properties of biocomposites are highlighted. Further, FVW biocomposites and their applications

Fig. 16.2 Type of wastage generated from fruits and vegetables

in food packaging systems that have a promising potential for an environmental sustainability approach for future work were discussed.

2 Food Wastage Footprint and Climate Change Report

FAO reported that about one-third of the total food produced for consumption is wasted or lost (FAO 2013). Food waste refers to food suitable for human consumption that is discarded, whether or not it has been kept past its expiry date or has been allowed to spoil. This food waste is frequently due to food spoilage. Food wastage is defined as any food that has been lost due to deterioration or waste. As a result, "wastage" refers to both food loss and food waste (FAO 2013).

First and foremost, food waste has an environmental impact due to the unnecessary waste of scarce land, water, and energy resources and as a factor in climate change. For every kilo of food formed, 4.5 kilos of CO_2 are generated and poured into our atmosphere. All environmental assessment commodities are based on a life cycle approach encompassing the entire "food cycle" (Scialabba 2015).

2.1 Climate Change Report

A food product's carbon footprint is the total amount of GHG (greenhouse gases) discharged during its life cycle, expressed in kg of CO_2 equivalents. This calculation includes GHG discharges from the production phase as well as subsequent phases. Thus, 1 kg of wheat and 1 kg of beef have different carbon footprints because their life cycles vary, releasing different types and amounts of GHG.

3 Preparation Methods of FVW-Based Biocomposites/Biofibers

About 25% of all vegetables and 15% of all fruits are wasted during the food production and supply chain (MohdBasri et al. 2021). Underutilized wastes (seed, peel, rind, and pomace) may contain valuable bioactive compounds, vitamins, dietary fibers, and oils. FVWs are high in nutrients, which help to develop bioactive ingredients and ethanol. Biocomposites are made from natural fillers/fibers (MohdBasri et al. 2021). The fibers found in the peel, seeds, and pomaces of FVW are used as filler in the biocomposites to improve their properties (Sohany et al. 2021). The peel and seeds possess more phenolics than the fleshy parts (Bayram et al. 2021). Mango peel, for example, has a higher phenolic content than mango flesh.

Additionally, citrus fruits have many organic wastes from the peel (MohdBasri et al. 2021). The conversion of these wastes into packaging materials provides an essential alternative to conventional plastic packaging while also contributing to a more sustainable environment. The biocomposites produced from different types of FVWs are elaborated in Table 16.1 with their functionalities.

Chen et al. (2012) conducted a study to develop cellulose nanocrystal from potato peel as a vapor barrier. Here cellulose nanocrystal was developed from potato peel

Table 16.1 Different biocomposites from fruit and vegetable wastes

Biocomposites	Types of fruit and vegetable wastes	Function	References
Polylactic acid	Carrot pomace	Increased thermal and mechanical properties; antibacterial activity	Szymańska-Chargot et al. (2020)
Potato peel powder–LLDPE biocomposite	Potato peel	Increased tensile strength	Sugumaran et al. (2017)
Films with polyvinyl alcohol	Apple pomace	Increased thermal stability; reduced tensile strength	Gaikwad et al. (2016)
Potato peel waste fermentation residue	Potato peel	Increased biodegradability	Wei et al. (2015)
Polypropylene-potato peel biocomposites	Potato peel	Increased thermal and physicomechanical properties	Sugumaran et al. (2015)
Cellulose nanocrystals	Potato peel	Enhanced mechanical and barrier properties	Chen et al. (2012)
Polyvinyl alcohol composite	Jackfruit peel flour	Improved biodegradability	Ooi et al. (2011)
Film	Sweet potato starch and sweet potato peel	Increased thickness, water solubility, and swelling degree of the films	Sohany et al. (2021)

LLDPE Linear low-density polyethylene

based on acid and alkali treatment. PepsiCo UK, a well-known potato chips company worldwide, generates a tremendous amount of waste in the form of potato peels. Byrne (2012) studied the feasibility of utilizing starch from this potato peel waste to develop crisp packaging material. Mango waste is mainly generated in two forms basically, 14–22% in the form of seed and 11–18% in peel. Other than this, wastes from papaya, pineapple, and jackfruits are also being used for biocomposite formation (Choudhary et al. 2019).

3.1 Injection Molding

Biocomposites are typically formed in two stages. Following the first stage (compounding), the manufactured granulate is processed into components in an injection molding process. The injection molding compounder is an alternative to this two-step process. Compounding is done using a co-rotating twin-screw extruder having a similar configuration as the conventional method. First, the polymer is dosed in an extruder casing and melted using a gravimetric dosing system. Second, the long fibers are moved from coils and then dosed at the center of the extruder. The polymer and fibers are then homogenized. The composite would be cooled and formed into pellets in a traditional compounding process.

On the other hand, the injection molding compounder uninterruptedly feeds the melted mixture into a melt reservoir. The composite then moves into the shot-pot, an injection unit similar to a plunger injection molding machine. The following steps are similar to those of a traditional injection molding process. The injection molding compounder process has advantages over traditional compounding and injection molding methods.

By gentle compounding, the injection molding process reduces the shortening of the mechanical properties of fibers. Compared to traditional preparation and processing methods, components with longer fibers and better mechanical properties can thus be realized. Higher mechanical properties can also be obtained from the one-time thermal stress exposure of the plastic and natural fibers. Another advantage of injection molding compounder is quickly changing or adjusting the fiber ratio (Feldmann and Fuchs 2016).

3.2 Compounding/Compression Molding

The compression molding technique has been extensively used to develop biofilms that do not require the use of any solvent or binder. The FVWs are exposed to high temperatures and pressures in a heated press using this technique. Furthermore, the molding method is better suited for industrial applications because it requires less energy and takes less time to complete than other techniques such as solution casting (Acquavia et al. 2021). Gurram et al. (2018) used compression molding technology to produce biofilms from citrus peel pectin. In recent years, FVW has been fascinated by natural fibers that can be used as reinforcing elements in biodegradable biocomposite materials. Biopolymers can be obtained from a wide range of fruits and vegetables, exhibiting several distinct properties not found in conventional fibers (Acquavia et al. 2021). Schettini et al. (2013) produced a novel biocomposite using peels of hemp and tomato and seed fibers as a natural support for sodium alginate to create biodegradable pots in agriculture. Mathivanan et al. (2016) used various concentrations of pineapple leaf fibers to reinforce cassava biocomposites resin *via* extrusion using hot compression molding. The 30% composition had the highest average modulus value among the other compositions, implying that the addition of pineapple leaf fibers increases the modulus strength of the composite.

3.3 Compounding/Film Formation

Casting forms biocomposites from film formation. This method calls for a polymeric solution to be poured into a mold and dried at room temperature. Various combinations of starch and polyvinyl alcohol (PVA) are also used to form films. Starch, a biodegradable material, has superior film-forming properties that are inexpensive, versatile, and widely available. PVA, a water-soluble polymer, is formed through the polymerization and hydrolysis of vinyl alcohol with high film strength. Apple, blueberry, rambutan, cranberry, acai berry, pineapple, mango, jackfruit, and citrus wastes have all been used to develop biocomposites and films (Gowman et al. 2019). Gaikwad et al. (2016) developed antimicrobial apple pomace/PVA films using DPPH (2,2-diphenyl-1-picrylhydrazyl) assay. The apple pomace/PVA film with 30% apple pomace had a scavenging activity of 40%, whereas the control with only a PVA film had no scavenging activity. This result demonstrated that the apple pomace films possess good antioxidant activity. The film formation method was also used to prepare cellulose nanocrystals filled with PVA and thermoplastic starch (Chen et al. 2012). This method of preparation achieved uniform dispersion of 1–2% (w/w) filler content. Chen et al. (2012) found an increase in tensile modulus from 19% to 33% for PVA and 38% to 49% for starch composite, respectively. There was a minimal reduction in water vapor transmission rate for PVA composite developed, and no change was found for the thermoplastic composite (Chen et al. 2012). In another study, a biofilm from cassava starch and blueberry pomace was developed (Luchese et al. 2018). They observed that adding blueberry pomace to their films resulted in high absorption of wavelengths less than 300 nm, signifying that the pomace could protect the films from UV light. Zhong et al. (2011) studied the film formation with PVA, glycerol, hexamethylenetetramine, polysorbate 80 as a matrix material, and rambutan peel flour at a filler content of 8% to 32%. Tensile strength decreased as rambutan flour content increased. The water absorption was enhanced because of the filler's hydrophilic nature (Zhong et al. 2011). From the peel and the seed of mango, a significant amount of waste can be produced. Lima et al. (2019) fabricated poly-lactic acid (PLA) films with mango seed fiber. The presence of starch and cellulose in the samples caused a shift in peaks in the composite's X-ray diffraction patterns. Surprisingly, the seed fiber increased the tensile strength and Young's modulus of the PLA film. The increased modulus was attributed to forming an anchoring surface between the cellulose fibers of the mango parts and PLA, which resulted in improved stress transfer in the system (Lima et al. 2019). Deng and Zhao (2011) fabricated bio-based food-grade films by combining fresh red grape pomace with polysaccharides. The films' main components were a polysaccharide mixture (sodium alginate, carrageenan, and cellulose gum) and low methoxyl pectin. To act as a plasticizer, glycerol was added to some blends. Overall, pomace served as an effective colorant in the films while also acting as a water barrier. Meanwhile, the biocomposites' mechanical properties were satisfactory (Deng and Zhao 2011).

3.4 Improving Basic Mechanical Properties and Functionalities

The functional and mechanical properties of biocomposites improve using FVWs due to their functionalities like antimicrobial properties (Acquavia et al. 2021). Preservative effects such as antimicrobial activity, anti-inflammatory, and antioxidant properties are provided by the presence of phytochemicals and bioactive compounds (MohdBasri et al. 2021). It has been discovered that adding additives to polymers improves their mechanical and barrier properties. Polymers can also function as pH indicators or antimicrobial films depending on the presence of additives (Ali et al. 2019). An evaluation of biocomposites' mechanical and physical properties is required to assess their suitability to determine their life cycle. The ultimate tensile strength, Young's modulus, and elongation at break are the main mechanical properties typically tested after producing a biocomposite. The tensile strength shows the maximum stress endured by any material before fracturing, whereas Young's modulus defines a material's stiffness: the greater the value, the stiffer the material (Granda et al. 2016). The "elongation at break" refers to the material ductility and is affected by the crosshead speed and temperature. For hard materials, there is less or zero elongation at break value.

Conversely, materials with a higher capacity to withstand a high load without failure exhibit more excellent elongation than 100 percent (Acquavia et al. 2021). These properties are influenced by their chemical structure, the degree of polymer orientation, the crystallinity of the material, and the presence of fibers that act as reinforcement or plasticizers (Suderman et al. 2018). Plasticizers such as water, oligosaccharides, polyols, and lipids are used in edible films and coatings. Polyols are efficient plasticizers for hydrophilic polymers (Acquavia et al. 2021). Ooi et al. (2011) observed a reduction in tensile strength of PVA produced from jackfruit waste as filler loading increased. However, as the amount of jackfruit waste increased, Young's modulus improved, indicating that the filler represented as a stiffening agent (Ooi et al. 2011). Rogols et al. (2002) developed an adhesive and binder-based potato peel to develop packaging material. They claim that there are various applications of these biocomposites in the food packaging industry. As a binder, it helps produce composite food, meat and vegetable analogs, and protein- and fiber-rich food products (Rogols et al. 2002). Also there are some reports about biodegradable biopolymer production of polyhydroxyalkanoates from fruits and vegetables (Cinelli et al. 2019; Rebocho et al. 2019). In another study, potato peel waste fermented residue fibers were utilized to prepare biocomposite with polyhydroxybutyrate (PHB).

The physical, mechanical, and thermal properties were investigated with suitable analytical instruments, and it was found that biocomposite has poor mechanical strength but has a high biodegradation rate compared to PHB. The biodegradability was maximal, with a fiber content of more than 15%. It was observed that the degradation rate is directly proportional to the fiber content (Wei et al. 2015). Gurram et al. (2018) reported that the addition of up to 20% fungal biomass increased the tensile strength (16.1–19.3 MPa) and decreased the water vapor permeability of the pectin films (Table 16.2).

All of the processing methods chosen for the production of food waste–based biocomposites impact their final properties. In many cases, the various biocomposites must be blended with additives to optimize material properties such as thermal instability, high water vapor, brittleness, and low melt strength. However, biocomposites are finally processed to produce biofilms or 3D objects using traditional mechanical techniques such as extrusion, molding, film formation, or a combination of these (Acquavia et al. 2021).

4 Fruit Wastes in Biocomposites

The judicious use of fruit waste resources for biocomposite manufacturing is therefore entirely justified and potential. The raw materials utilized are high in proteins, polysaccharides, etc. Pomace obtained from juice extraction, grains from beer production, and oil cake after oil extraction, stem, and leaves can also be good sources of polysaccharides. Some promising raw materials that can be used to enrich the overall composition of biocomposites are apple, chokeberry, banana, acai berry, currant, kiwi, jackfruit, blueberry, cranberry, coconut, grape, durian, rambutan, olive, mango, passion fruit waste, pineapple, date, etc. due to their properties (Nawirska and Kwaśniewska 2005). Fruit and vegetable peels, seeds, and pomace include fibers employed as filler in the film matrix to increase biopolymer characteristics (Luchese et al. 2018). Pectin is another waste-derived component that is employed in the polymeric matrix (Dash et al. 2019). Furthermore, the peel and seeds contain more phenolic chemicals than the fleshy portion of the fruit.

Table 16.2 Improved mechanical and functional properties of biocomposites from fruit and vegetable wastes (FVWs)

Source of FVWs	Type of biocomposites	Preparation method	Improved mechanical and functional properties	References
Banana peels	Pectin-based biofilm	Film formation	Tensile strength (MPa): 7.92–1.21 Elongation at break (%): 4.26–0.77	Oliveira et al. (2017)
	Biocomposite	Film formation	Tensile strength (MPa): ~5 to ~39 Elongation at break (%): ~1 to ~9	Faradilla et al. (2018)
	Biocomposite	Film formation	Tensile strength for chemical-based material (MPa): 0.228 Tensile strength for natural-based material (MPa): 0.150 Young's modulus for chemical-based material (MPa): 1.53 Young's modulus for natural-based material (MPa): 1.88 Elongation at break for chemical-based material: 18.77% Elongation at break for natural-based material: 13.97%	Azieyanti et al. (2020)
Cassava peels	Biocomposite	Film formation	Tensile strength (MPa): 35.28–96.04 Elongation at break (%): 14.87–52.27 Water resistance (%): 22.68–78.40	Fathanah et al. (2018)
	Biocomposite	Film formation	Tensile strength (MPa): 0.40–2.68 Elongation at break (%): 30.37–94.25	Dasumiati et al. (2018)
Carrot waste	Cellulose-based biofilm	Film formation	Young's modulus (MPa): ~1300 Elongation at break: 6% Ultimate strength (MPa): ~37	Perotto et al. (2018)
Citrus waste	Pectin-based biofilm	Molding	Elongation at break with fungal biomass (%): 1.4–4.5 Young's modulus (MPa) with fungal biomass: 187 1350	Gurram et al. (2018)
Hemp fibers	Biocomposite	Molding	Young's modulus (MPa): 62.51–97.08 Tensile stress at break (MPa): 0.46–1.20	Schettini et al. (2013)
Orange peels	Pectin- and cellulose-based biofilm	Film formation	Tensile strength (MPa): 28–36 Time for 90% degradation: 15 days	Bátori et al. (2017)
Jackfruit peel flour	Polyvinyl alcohol composite	Solution casting	Young's modulus (MPa): 157–196 Water absorption capacity: 10% Water transmission rate: 46%	Ooi et al. (2011)

4.1 Pomace Utilization in Biocomposites

There is currently interest in employing the pomace for functional foods, food processing, cosmetics, medicines, and supplements. However, there has not been much study done on its use for polymer fillers (Dwyer et al. 2014).

4.1.1 Apple Pomace

The global production of apples in a million tons is 74.2 million tons, with total waste generated as 14.8 million tons (USDA 2018). Cranberry, blueberry, and apple pulps were used to make reinforced molded pulp boards for packing by Gouw et al. (2017). These writers distinguish between structural and nonstructural components in fruits and vegetables, for example, lignocellulosic versus pectins and extractable chemicals such as phenolics. They further note that cellulose levels in pomaces or lignocellulosic materials more than 30% are more likely to be used to produce composites. In this study, the cellulose content of apple pomace was reported to be 70%. The authors claimed that the successfully made boards contained newspaper pulp and pomace ratios of 1:1.

In comparison to the other pomaces tested, apple pomace exhibited similar qualities. However, because of the presence of pectin in 19% of AP, water retention was somewhat more significant than in other pomaces. This is somewhat greater than the data observed in 2–15 percent of the literature (Dash et al. 2019). In general, these authors' reported method of this work has the benefit of being undertaken in moist circumstances. It may or may not be influenced by the quality of the pomaces as a result of chemical derivatizations. A study conducted by Gaikwad et al. (2016) described the fabrication and general characteristics of a composite consisting of PVA and apple pomace utilizing the casting method. These writers report the inclusion of the apple pomace up to 30% of the total weight of the composite in terms of production. The apple pomace was dried and ground first, but the particle size of the apple pomace powder was not specified at the end. These authors discovered the films' thickness and the oxygen transfer rate as the apple pomace concentration grows.

4.1.2 Grape Pomace Utilization in Biocomposites

The global production of grapes in a million tons is 23.4 million tons, with total waste generated as 5.85 million tons (USDA 2018). Grape pomace may include skin, flesh stems, seeds, etc., obtained from winery industries. Grape seeds have been utilized in different proportions in a PLA matrix by Spiridon et al. (2015). However, grape pomace has not been employed in a bio-polybutylene succinate (PBS) matrix. Bio-based food-grade films were designed by combining fresh red grape pomace with polysaccharides by Deng and Zhao (2011). The key ingredients in the films were polysaccharide combination (of sodium alginate, carrageenan, cell, and cellulose gum) and low methoxyl pectin. Glycerol was used as a plasticizer in some mixes. Overall, pomace worked well as a colorant and a water barrier in the films. Grape peels were used in a soy flour matrix by Jiang et al. (2011), who discovered that the grape skins might generate biodegradable composites. Both groups conducted flexural testing on such materials and found adequate breaking strength, but no other mechanical attributes were assessed (Jiang et al. 2011).

5 Vegetable Waste Used in Biocomposites

According to the literature review, little research has been done on the use of vegetable waste or kitchen trash (onion, potato, and carrot peel) as fillers in polymer resin. Chen et al. (2012) looked into the use of cellulose nanocrystals generated from potato peel waste as a vapor barrier and reinforcement in polyvinyl alcohol and thermoplastic starch composites. The reinforcement with 1% and 2% cellulose nanocrystals increased the tensile modulus of starch composites by 19% and 33%, respectively, and PVA composites by 38% and 49%. Furthermore, whereas the PVA composite showed a considerable reduction in water vapor transmission tests, the thermoplastic starch composite showed no impact. In a study by Szymańska-Chargot et al. (2020), a nanocomposite made of PLA and nanocellulose from carrot pomace, modified with silver nanoparticles, was prepared, and increased mechanical, hydrophilic, thermal, and antibacterial activities were observed. After the industrial extraction of starch, Vannini et al. (2021) sought to valorize the solid portion of sweet potato rich in starch and fibrous components (pectin, cellulose, hemicellulose, and lignin). The sweet potato residue was then supposed to be used to create novel biocomposites for use in food packaging. This fraction was added to poly (3-hydroxybutyrate-co-3-hydroxyvalerate) in various concentrations ranging from 5 to 40% by melt mixing at two different processing temperatures and times: 200°C for 5 minutes or 180°C for 6 minutes. In another study by Mardijanti et al. (2021), cocopith waste was incorporated into wood powder and tapioca matrix to prepare a myceliated biocomposite, and it was observed that the biocomposite showed increased thermal conductivity.

6 Applications of Biocomposite from FVWs in Food Packaging

The food packaging industry accounted for around 60% of all plastic manufacturing (FAO 2019). They contaminate the environment and impair human health by accumulating nondegradable plastics and forming secondary microplastics and toxic compounds during manufacture and usage due to this inadequate recycling.

The utilization of biodegradable packaging materials is now in trend due to increased consumers' demand and environmental concerns. There has been much focus in recent years on finding alternative polymer materials as added-value new packaging materials through FVW valorization. This will minimize the quantity of food packaging waste and the amount of trash and by-products produced from fruits and vegetables. Due to its unique properties, food packaging made from FVWs and by-products is gaining appeal. When used in food packaging systems, these wastes and by-products offer several benefits, including increased antioxidant activity, antibacterial activity, improved mechanical properties, and improved food product quality (Peelman et al. 2013). Several researches have looked at using these wastes in biopolymers, biocomposites, active packaging systems, intelligent packaging systems, and edible films and coatings to improve package quality.

6.1 Edible Films and Coatings

Although edible films and coatings are frequently used interchangeably, they are applied differently (Krotchta and De Mulder-Johnston 1997). Films are stand-alone structures manufactured separately and then placed on the surface of food or between food components or even sealed into edible pouches. On the other hand, edible coatings are applied directly to food surfaces by dipping, spraying, or panning, the latter of which is accomplished by mixing both the food and the coating solution in a spinning bowl and then drying (Krotchta and De Mulder-Johnston 1997). Because of their use and nature, plant-derived bioactive chemicals are being recognized as exciting materials for the fabrication of biodegradable and bioactive films. FVWs are an excellent gift for the packaging industries in making edible films and coatings due to their antioxidant and antimicrobial activities (Khorasani and Shojaosadati 2017; Nogueira et al. 2020). Nogueira et al. (2020) studied the development of edible coating by incorporating blackberry pulp extracts into film-forming solution by casting method and observed that water vapor permeability and solubility in water increased by reducing tensile strength.

6.2 Eco-friendly Composite

After being combined with food wastes, eco-friendly biocomposites can attain end-of-life biodegradation and are readily handled. Composites are custom-made materials with a one-of-a-kind quality, with qualities that may be changed by changing the reinforcing and matrix phases (Bledzki and Gassan 1999). Natural fibers offer several advantages over synthetic fibers owing to their quantity, availability, and inexpensive cost. Natural fibers are less dense (1.2–1.6 g/cm^3) when compared to other synthetic fibers and are biodegradable, so they are excellent for making eco-friendly composites (Madhu et al. 2020). Natural fibers can be obtained from agro-industrial wastes and are incredibly lightweight. Eco-friendly packaging may be made from several plant fibers, including pineapple, banana, jackfruit, mango, jute, and flex. The pineapple leaf fiber is a critical agricultural processing waste material that is made up of hemicellulose (80–82%), lignin (10–12%), and ash (1–3%). Pineapple leaf fiber has outstanding mechanical qualities and may be utilized to make reinforced polymer composites. The addition of 10–30% lemon peel powder and sweet lime peel powder to natural fibers and epoxy resins strengthens their mechanical strength, according to Patil et al. (2018). The epoxy-lemon biopolymer, which contained a 30% volume weight of lemon particles, showed optimal mechanical performance. Cellulose, lignin, and crude fibers, which comprised about 90% of the sweet lime and lemon, were associated with improved mechanical qualities. Khoozani et al. (2019) employed oven drying, a spouted bed drier, ultrasound, a pulsed vacuum oven, a microwave, spray drying, and lyophilization to create flour from banana pulps and peels.

Additionally, edible coatings were developed using flour prepared from ripe "Prata" banana (*Musa* spp.) peels. Ooi et al. (2011) reported that the flour formed after drying the jackfruit by-products might be utilized to make food packaging. Biodegradable packaging films may be made by combining these biocomponents with appropriate synthetic polymers.

6.3 Antioxidant and Antimicrobial Properties of Packaging and Biocomposite Systems

Fruit peels and seeds, such as those from grapes, pomegranates, avocados, and citrus, are the most utilized vegetable by-products because they prevent oxidation (lipid and protein) and formation of pathogenic and degrading bacteria in the food supply. When these by-products are added to meat products, the quality of the product can sometimes be improved while the shelf life is extended (Figueroa et al. 2020). The amount of phenolic in wastes also varies. Avocado peel, for example, has a greater phenolic concentration than the seed and pulp (Rodríguez-Carpena et al. 2011). Pectin is another waste-derived value-added chemical that might be used as a polymeric matrix for active packaging. Pectin is used as a thickener, stabilizer, and texturizer with the potential to produce gels. It is compatible with proteins, lipids, and polysaccharides, and it boosts the antioxidant and antibacterial properties of active packaging materials. Starch, on the other hand, is seen as a precious commodity (Chel-Guerrero et al. 2016). Some of the examples of fruit and vegetable wastes used in packaging due to their antimicrobial, antibacterial, and antioxidant properties are shown in Table 16.3.

Table 16.3 Antimicrobial and antioxidant property of some fruit and vegetable wastes

Film formed	Property	Product packaging	References
Chitosan/citric acid + chitosan/ carboxy methyl cellulose	Antimicrobial activity	Strawberries	Yan et al. (2019)
Chitosan + grape seed extract	Antimicrobial property	Rainbow trout fillet	Hassanzadeh et al. (2018)
Zein film + pomegranate peel extract	Antimicrobial property	Cheese	Mushtaq et al. (2018)
Composite films ASP/CMC + apple skin (powder, extract)	Antimicrobial activity against *Listeria monocytogenes*, *Streptococcus aureus, Salmonella enterica*, and *Shigella flexneri*	–	Choi et al. (2017)
Potato peel film + bacterial cellulose (BC) + curcumin	Antimicrobial activity	–	Xie et al. (2020)
Tomato by-product extract added to films containing polyvinyl alcohol (3% w/v) and chitosan (1% w/v)	Improved antibacterial activity toward *S. aureus* and *Pseudomonas aeruginosa*, ↑ resistance of films, ↑ antioxidant activity	–	Cerruti et al. (2009)

6.4 Applications of FVW in Product Packaging

Uranga et al. (2019) used chitosan and citric acid to make antibacterial films, including fish gelatin in the mix. The films are antibacterial against *E. coli*, operate as an ultraviolet ray barrier, and have solid mechanical qualities, and the citric acid works as a swelling inhibitor when exposed to water (Choi et al. 2017). Nair et al. (2018) studied the effect of chitosan and alginate-based coatings enriched with pomegranate peel extract to extend the postharvest quality of guava (*Psidium guajava* L.) and observed that postharvest guava quality was improved with increased antioxidant activity and delayed senescence. Torres-León et al. (2018) prepared edible film-containing mango peel flour (1.09%), glycerol (0.33%), and extract of mango seed (0.078 g/L) and applied to the peach fruit and observed increased permeability, antioxidant activity, hydrophobicity, and surface properties. Pereira Jr et al. (2015) designed active chitosan/PVA films with anthocyanins from *Brassica oleracea* (red cabbage), which were prepared and applied to milk, and an increased tensile strength moisture retention and high antibacterial effect were observed.

7 Environmental Sustainability Approach

Waste valorization with an environmentally sustainable approach is essential. The FVWs are sustainable raw materials that can be used to develop several value-added products using green technology. The production of FVW-based biocomposites can be a sustainable technique for waste valorization, and it is also economical.

7.1 Release of Degraded Products

After manufacturing a product out of an environmentally friendly biocomposite, it must meet certain objectives, such as not causing harm to the environment and maintaining human health over the product's life span. Biocomposites may emit volatile and low-molecular-weight components, which may affect food products packaged in them as well as the environment. The polymer matrix may contain different types of volatile and low-molecular-weight components from different sources. During synthesis, there may be chances of retainment of polymerization residue. There may be the release of additives like stabilizers incorporated to improve the properties of the polymer matrix and contaminants entered during manufacturing. During storage and throughout the life span, the polymer may produce different degraded products at various stages, which can enter and cause a hazard to the environment. FVW-based biocomposite can produce low-molecular-weight components during thermal processing. They have low thermal stability from either polymer matrix or reinforcing agent, which can be lignocelluloses. Therefore, unpleasant odor might be released, which would restrict its application in food packaging. Usually, natural fibers from FVWs degrade at 200°C (also below the given range). Therefore, volatile components will be produced if thermal processing is beyond this temperature. These natural fibers are processed thermomechanically, same as synthetic fibers, using extrusion, injection molding, and compression molding. Interaction between various components in biocomposite and their effect on thermal strength is still not clear.

7.2 Effect of Released Particles on Environment

It has been observed that various phenolic components are produced from biocomposites. In order to achieve desirable thermal and barrier properties of the natural polymer matrix, some nanoparticles are also added to, which may release and cause a toxicological effect on the environment. Furthermore, there is an issue with the migration of nanoparticles in the case of nano-biocomposites, which may enter food packed in it. Nanoparticles with antibacterial activity are used as fillers to improve their functional property. However, the adverse effect is that it may exhibit oxidative stress in animal tissues and cytotoxicity and accumulate in organs. Minimal size and high surface area of these nanoparticles will lead to faster movement through the body and, ultimately, faster toxic interaction with human tissue. More exfoliation degrees will reduce the release of nanoparticles, as the tortuous path will increase. So to prevent this release, some surface treatments are given to the reinforcing agent. Migration limit for the nanoparticles into food is observed, and it has been reported that it is within the limit, 60 mg/kg set by European legislation (Boland et al. 2014; McClements 2020). In order to know about environmental sustainability and its advantages to the environment, a life cycle analysis (LCA) is conducted.

7.3 Circular Economy

Globally researchers are trying their best to reduce conventional plastic by replacing it with bioplastic and biocomposites or plastic incineration. Major drawbacks of plastic incineration are taken into consideration, such as it affects air and water and releases harmful chemicals and toxins into the environment in which we live during the process (Yang et al. 2021; Qureshi et al. 2020). There are many challenges to plastic recycling. It includes collecting and identifying plastic waste and separating plastic based on melting point because phase separation may occur, and therefore use of biocomposite is one of the reasonable solutions. Biocomposites are renewable and biodegradable and can replace nonbiodegradable materials. Also, it ensures the appropriate application of biodegradable waste. Demand for biocomposites is increasing, and it can be accomplished by using FVW to produce biocomposites (Plastic Market Size, Growth and Trends Report, 2021-2028, 2021). The circular economy includes raw material processing, manufacture, use, disposal, and recycling (Fig. 16.3). Here circular economy in biocomposites will allow the recycling of FVW. The primary intention of the application of circular economy is to maintain environmental sustainability by reducing food waste and keeping resources at their required highest level (Den Hollander et al. 2017; Loiseau et al. 2016). Nevertheless, the implementation of circular economy in biocomposites needs much effort because of characteristic interaction between matrix and filler, which leads to challenging and expensive separation (Zhou et al. 2019). The circular economy perspective in FVW-based biocomposite recycling can give an appropriate reason for the fruitful recycling of polymer matrix and filler (Sauerwein et al. 2019).

7.4 LCA (Life Cycle Analysis) of FVW-Based Biocomposites

LCA or assessment is a methodology used to assess the environmental consequences of all stages of product development, from production to discarding. In order to disclose restrictions and impact of the product on global warming, use of water,

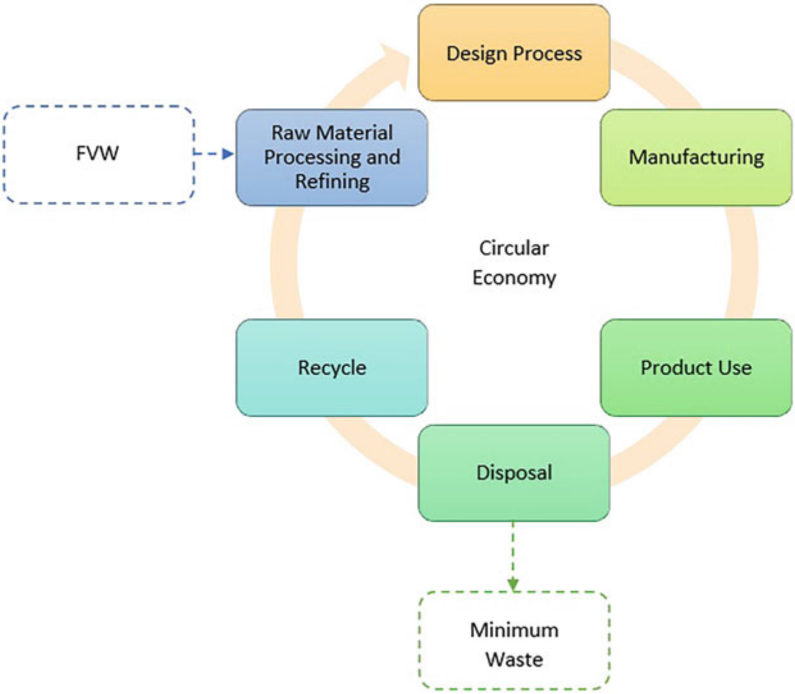

Fig. 16.3 Circular economy in FVW-based biocomposites

acidification, energy, climate change, etc. can be measured by using LCA to check product in circular economy representation, so necessary actions are taken for continuous upgradation. ISO 14040–ISO 14044 series contains a document of the agreement for the commission of life cycle analysis.

LCA has three main perspectives such as C2F, C2C, and C2G

- C2F: cradle to factory
- C2C: cradle to cradle
- C2G: cradle to grave

In order to analyze limited product life, the C2F approach is used, while the product's complete life cycle can be analyzed in the C2G approach. The remaining C2C approach also analyzes the product's complete life if the product is completely recyclable and made of biocomposite, which is biodegradable. Of these three approaches, cradle-to-cradle and cradle-to-grave are widely used in LCA (Stoiber et al. 2021; Ramesh and Vinodh 2020; Ghosh et al. 2020). When the LCA study used to assess the FVW-based biocomposites, it benefits the environment and economy compared with conventional reinforcement. There is a reduction in the emission of GHG when plant-based fibers are reinforced into the matrix.

Despite biocomposite made from waste having enhanced feasibility, it is crucial to restate that FVW-based biocomposite will not affect the biodegradability of synthetic polymers. However, in some cases, the use of natural fibers would lead to demerits if it contains pesticides and fertilizers. Therefore, recycling of nonbiodegradable matrix is not sustainable (Boland et al. 2014).

8 Conclusion and Future Perspectives

FVWs can be fruitfully reinforced into various types of environment-friendly polymer matrices like PHA, PLA, starch, and protein. FVWs support the valorization of by-products, making a profit for producers and products manufactured at a meager price. FVW-based biocomposites have several advantages. They can be manufactured at a meager cost compared to neat biopolymers. They are biodegradable and renewable, which reduces environmental pollution and product price due to low price reinforcing material. Despite these advantages of applying biocomposites made from FVWs, it should be considered during large-scale manufacturing that they have a low barrier and thermal properties than neat polymer. Some surface treatments can enhance these properties to the reinforcing agent, but it would result in higher manufacturing costs. Therefore, some costly stabilizers are used to improve these properties, stabilizing blends of non-miscible polymers. Further research using biocomposites from fruit and vegetable wastes in real life is needed, like research on additives used to improve barrier and thermal properties, which will ultimately reduce environmental pollution.

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Chapter 17
Biofuel Production from Vegetable and Fruit Wastes: Creating a Circular Economy

Preshanthan Moodley and Cristina Trois

Abstract The steep rise in the global population has placed immense strain on several sectors such as agriculture and food, waste management, climate change, and energy demand. Global demand for fuel has received much attention owing to the dwindling supply of fossil fuels such as oil and coal. For this reason, biofuels appear as an attractive alternative since it is a renewable and sustainable source of energy. In recent years, fruit and vegetable wastes (FVWs) have been earmarked as a feasible feedstock for biofuel processing since they are highly fermentable with high sugar content. Currently, FVWs are disposed of in landfills, where their decomposition plays a significant role in greenhouse gas emissions and the production of toxic leachate. Several studies have explored the production of bioethanol, biomethane, biohydrogen, biobutanol, and biodiesel from FVWs with varying results. This paper presents an up-to-date review of the literature through the lens of practical application. Employing FVWs in biofuel production processes would significantly reduce the burden that the current disposal method has on the environment while simultaneously providing a renewable and sustainable solution to the ever-increasing demand for energy,

Keywords Fruit and vegetable wastes · Pretreatment · Biofuels · Bioethanol · Biogas · Biobutanol · Biodiesel · Biohydrogen

1 Introduction

Global demand for fuels is increasing exponentially owing to the rapid depletion of conventional fossil fuels. However, these fuels have a finite supply, and coupled with the negative impacts of their combustion, alternatives are being explored. Biomass fuel derivatives are considered highly advantageous since they are sustainable and renewable and have significantly lower carbon footprint (Bogmans et al.

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2020). In this regard, organic waste is often viewed as an attractive feedstock for biofuel processes.

The fruit and vegetable market accounts for one of the most significant fractions of organic waste. The United Nations Food and Agriculture Organization (FAO) approximates that 1.3 billion tons of food are wasted annually, with fruit and vegetables comprising 60% of this total waste (Plazzotta et al. 2020). Fruit and vegetable wastes (FVWs) pose significant environmental problems due to their high biodegradability and moisture content. A majority of these wastes is disposed of in the landfill and subsequently contributes to the production of landfill leachate (Mishra et al. 2018). In addition, FVWs are also responsible for an estimated 8% of global greenhouse gas emissions following decomposition in landfills (Esparza et al. 2020). For these reasons, FVWs are being investigated as potential feedstocks for biofuels. However, a significant hindrance in this scenario is the lignocellulosic composition of FVWs. Lignin is highly recalcitrant, which thus hampers microbial degradation and enzymatic saccharification of the cellulose and hemicellulose components. For this reason, pretreatment is often considered an important stage in any bioprocess to enhance sugar yields and, ultimately, biofuel yields (Moodley and Kana 2017).

Biofuels such as bioethanol, biohydrogen, and biomethane have several key advantages over conventional fuels. These include a relatively cleaner-burning profile, high energy potential, and reduced burden on the environment. Additionally, the combustion of these fuels has lower carbon footprints, thus significantly contributing to the transition towards the green economy. Biofuels also have the added advantage of being produced from various waste feedstocks such as fruit and vegetable waste. This scenario is a starting point for contributing towards a circular economy, as illustrated in Fig 17.1.

2 Fruit and Vegetable Waste as a Feedstock

The twenty-first century has presented many challenges globally, some of which fall within the agricultural and food sector, where food security and waste management are highlighted as significant (Esparza et al. 2020). The FAO estimates that 780 million tons of fruit and vegetable wastes are generated annually (Plazzotta et al. 2020). For example, Brazil accounts for almost 36% of global fruit production, where most of this is channeled towards concentrated juice manufacturing. This manufacturing process generates 40–50% of gross waste weight, comprising peels, seeds, pulps, and kernels (Dos Santos et al. 2020). South Africa is another major fruit producer with 2.1 million, 1.8 million, and 0.79 million tons of citrus, grapes, and apples, respectively. The processing of these fruit streams results in large quantities of waste. For instance, an estimated 25–35% of processed apples, 50% citrus, and 20% grapes end up being wasted (Khan et al. 2015). Furthermore, most FVWs are produced during the harvesting and processing stages in developing countries, whereas the consumption stage produces minimal waste (Esparza et al. 2020).

Fig. 17.1 Schematic illustrating a circular economy concept for biofuel production

The disposal of FVW occupies an ever-increasing space in waste facilities and landfills, thereby becoming an environmental problem. FVWs are a significant type of residues because they are generated in large quantities in agricultural operations, supermarkets, and wholesale marketplaces. Due to sales losses, transportation, and disposal expenses, their production raises market operating costs (Pavi et al. 2017). FVWs are typical examples of lignocellulosic material owing to their composition. Lignocellulosic materials are highly recalcitrant and composed of cellulose and hemicellulose bound by a rigid lignin polymer. Cellulose and hemicellulose are made up of monomeric glucose units and xylose units, respectively. This indicates the fermentability of this material either indirectly *via* enzymatic catalysis or directly through microbial degradation. FVW has been employed as feedstock in various bioprocesses, as highlighted in Table 17.1.

3 Pretreatment of Fruit and Vegetable Waste

Pretreatment of FVW is an integral step in enhancing the bioavailability of sugars to valorize this waste into valuable precursors for complete biofuel production. The pretreatment process aims to disrupt the recalcitrant lignocellulosic matrix either on

Table 17.1 Biofuel production from different fruit and vegetable waste feedstocks

Feedstock	Biofuel	References
Mixed fruit waste	Biohydrogen	Sethupathy et al. (2019)
Fruit waste	Biohydrogen	Sethupathy et al. (2021)
Citrus peel waste	Biohydrogen	Camargo et al. (2021)
Potato pulp waste	Biomethane	Chen et al. (2021)
Cassava	Biomethane and biohydrogen	Cremonez et al. (2020)
Fruit and vegetable waste	Biomethane	Elsayed et al. (2021)
Citrus pulp	Biomethane	García-Rodríguez et al. (2020)
Potato waste	Biogas	Alrefai et al. (2020)
Cabbage waste	Biogas	Opurum (2021)
Orange peels	Biogas	Battista et al. (2020)
Grapefruit waste	Biogas	Magare et al. (2020)
Potato peel waste	Bioethanol	Chohan et al. (2020)
Carrot waste	Bioethanol	Khoshkho et al. (2021)
Apple waste	Bioethanol	Kut et al. (2020)
Banana waste	Bioethanol	Imteaz et al. (2021)

a molecular or physical level, ultimately improving the digestibility of the biomass towards enzymatic hydrolysis or through direct microbial degradation (Saha et al. 2018). Several studies have explored different pretreatment technologies on various FVWs, with some highlights shown in Table 17.2. Aruwajoye et al. (2017) investigated the pretreatment of cassava peels using a thermal soaking method. The cassava peels were first dried at 50 °C and milled to a particle size of 1–2 mm. The biomass was then soaked under optimal conditions at 69.62 °C for 2.57 h in water followed by a dilute acid pretreatment of 3.68 % HCl (with a solid loading of 9.65 %) at 121 °C for 5 min. A reducing sugar yield of 0.920 g/g was observed, significantly higher than previous studies on cassava peels. Citrus peels have also been explored as a feedstock with a potentially high sugar content to support biofuel production. John et al. (2017) optimized the pretreatment of citrus peels employing the Taguchi design to increase cellulose content. The peels were pretreated with 0.25 % sulfuric acid at a 17 % solid loading using an autoclave (121 °C) for 1 h. These optimum conditions gave an enhanced cellulose content of 35 %, corresponding to a yield of 7.09 mg sugar/ml of hydrolysate recovered. Many different pretreatment regimes have also been applied to banana peels. For instance, a recent study examined a combined acid and alkali pretreatment on banana peels (Rai et al. 2019). The pretreatment was optimized with the Box-Behnken design, and optimum conditions of 0.095 % H_2SO_4 and 0.05 % NaOH for 3 h gave a yield of 5243.62 μg/ml sugar. Another study compared the efficiency of acid and alkaline pretreatment on banana peels and found that acid revealed higher cellulose exposure (585.2 mg/g biomass), corresponding to a maximum glucose and xylose yield of 677.3 and 165.1 mg/g, respectively, after enzymatic hydrolysis (Mishra et al. 2020).

Table 17.2 Pretreatment technologies employed on fruit and vegetable waste

Feedstock	Pretreatment	Main finding	References
Banana peels	0.2 M acetic acid, 100 °C, 1 h	99.9 % sugar recovery	Saha et al. (2016)
Orange peels	0.2 M acetic acid, 100 °C, 1 h	97.9 % sugar recovery	Saha et al. (2016)
Mixed fruit waste	0.2 M acetic acid, 62.5 °C, 30 min	95 % sugar recovery obtained	Saha et al. (2018)
Banana peels	0.095 % H_2SO_4, 0.05 % NaOH, 3 h	5243.62 μg/ml sugar recovered	Rai et al. (2019)
Citrus peels	17 % solid loading, 0.25 %, H_2SO_4, 1 h	7.09 mg sugar/ml of hydrolysate recovered	John et al. (2017)
Cassava peels	2.57 h soaking at 69.62 °C, followed by 3.68 % acid at 121 °C for 5 min.	Maximum sugar recovery of 0.93 g/g observed	Aruwajoye et al. (2017)
Potato peels	1 % H_2SO_4 at 150 °C for 60 min	36 g/L sugar recovered	Abedini et al. (2020)

4 Biofuels from Fruit and Vegetable Wastes

Several types of biofuels are derived from FVWs. These are biohydrogen, biogas, bioethanol, biobutanol, and biodiesel.

4.1 Biohydrogen from Fruit and Vegetable Wastes

Biohydrogen is considered one of the cleanest biofuel alternatives since water is the only by-product in a fuel cell. Additionally, biohydrogen has an energy yield of 122 kJ/g, approximately 2.75 times greater than conventional hydrocarbon fuels (Sekoai and Daramola 2015). Several studies have investigated biohydrogen production from FVWs (Table 17.3), to promote a circular economy. For instance, orange peels pretreated with boiling water produced 1700 mL/L of biohydrogen using facultative anaerobe *Enterobacter aerogenes* (KY549389) (Abd-Alla et al. 2018). Another study examining banana peel waste found that after acid (0.095 %, H_2SO_4) and alkali (0.05 %, NaOH) pretreatment, a sugar yield and hydrogen yield of 5243.62 μg/ml and 43 ml H_2/30 ml media, respectively, were observed (Rai et al. 2019). Mahato et al. (2020) investigated the production of biohydrogen from fruit waste using *Clostridium* BOH3. These authors reported a hydrogen volume of 10720 mL/L, equating to 2.43 mol H_2/mol hexose yield. Potato waste was also shown to be an excellent substrate for biohydrogen production. Vi et al. (2017) reported an optimized hydrogen yield of 3501 mL/L at pH 6.05 coupled with a potato and $FeSO_4$ concentration of 27.63 g/L and 63.17 mg/L, respectively. Similarly, another study modeled biohydrogen production using an artificial neural network and response surface methodology. This study reported a hydrogen yield

Table 17.3 Biohydrogen yield from different fruit and vegetable waste feedstocks

Feedstock	H_2 yield	References
Orange peels	1700 mL/L	Abd-Alla et al. (2018)
Banana peels	43 mL/30 mL media	Rai et al. (2019)
Fruit waste	2.43 mol/mol hexose	Mahato et al. (2020)
Potato waste	3501 mL/L	Vi et al. (2017)
Potato waste	150 mL/g	Salem et al. (2018)

of 106.2 cm^3/g using sludge as the inoculum source (Wang et al. 2020). Salem et al. (2018) examined the effect of hydraulic retention time (HRT) on biohydrogen production from potato waste and found an HRT of 18h optimally yielded 150 ml H_2/g. A study comparing FVW, sugar beet pulp, and corn silage found that FVW gave the highest hydrogen yield of 52 cm^3/g VS (volatile solids) with an organic loading rate of 17 g VS/L/day (Cieciura-Włoch et al. 2020). These findings are indicative of the suitability of employing FVW for biohydrogen production.

4.2 *Biogas from Fruit and Vegetable Wastes*

Biogas is typically made of methane (CH_4, 55–80%) and carbon dioxide (CO_2, 20–45%), although smaller trace amounts of other gases such as ammonia (NH_3), hydrogen sulfide (H_2S), and vapor (H_2O) may be present (Ogejo et al. 2009). The methane component is solely responsible for generating energy, either through heat or electricity. Biogas production occurs most frequently through anaerobic digestion using different types of sludge or mixed microbial consortia as the source of inoculum. Generally, the composition of biogas is directly affected by the selection of organic feedstock employed in the digestion process. A recent study explored the combination of either FVWs coupled with slaughterhouse wastewater due to its rich microbial community, enhancing anaerobic digestion (Chakravarty and Mandavgane 2021). The two-stage anaerobic and aerobic process was completed in 30 days with biogas yields of 16 L/kg and 13.2 L/kg for the FVWs, respectively.

Additionally, these authors noted that the employment of *Trichoderma reesei* caused significant delignification of 64% and 70% for FVWs, respectively, thereby enhancing cellulose digestion. In another study, cabbage and mustard were compared in three different forms, viz., juice, residue, and their mixture for biogas production in batch reactors (Tang et al. 2020). Cabbage residue demonstrated the highest biogas yield of 800 mL/g VS. In contrast, mustard juice exhibited the lowest yield at 498 mL/g VS. Furthermore, the same study concluded that residue waste has the highest methane potential compared to their juice counterparts. Masebinu et al. (2018) investigated FVW ratios to determine the ratio for optimal biogas production. These authors reported that a ratio of 2.2:2.8 of FVW at an OLR (organic loading rate) between 2.68 and 2.97 kg VS/m^3-d resulted in 0.87 Nm^3/kg VS with 57.58% methane over 105 days. These findings suggest an interesting relationship between

Table 17.4 Biogas yield from different fruit and vegetable waste feedstocks

Feedstock	Biogas yield	Feedstocks
Fruit waste	16 L/kg	Chakravarty and Mandavgane (2021)
Vegetable waste	13.2 L/kg	Chakravarty and Mandavgane (2021)
Cabbage waste	800 mL/g VS	Tang et al. (2020)
Mustard juice	498 mL/g VS	Tang et al. (2020)
Fruit and vegetable waste	0.87 Nm^3/kg VS	Masebinu et al. (2018)

Table 17.5 Bioethanol yield from different fruit and vegetable waste feedstocks

Feedstock	Bioethanol yield	References
Potato straw	24%	Madadi et al. (2021)
Apple pomace	52.6 g/L	Demiray et al. (2021)
Apple pomace	0.44 g/g	Molinuevo-Salces et al. (2020)
Fruit waste	2.50 g/L/h	Zanivan et al. (2021)
Composite vegetable waste	125.6 mg/g	Chatterjee and Mohan (2021)
Sweet potato waste	251.85 mg/g	Chatterjee and Mohan (2021)
Potato waste	235.4 mg/g	Chatterjee and Mohan (2021)
Yam waste	240.98 mg/g	Chatterjee and Mohan (2021)

the ratios of fruit and vegetable, further indicating a significant effect on output yield, which warrants further investigation with the potential to examine specific wastes within the stream. Table 17.4 shows the biogas yield from different fruit and vegetable waste feedstocks.

4.3 Bioethanol from Fruit and Vegetable Wastes

Bioethanol is one of the most commercialized biofuels among the various alternatives. It is mainly used as a transportation fuel, often mixing in varying ratios with gasoline (İçoz et al. 2009). Bioethanol is a high octane fuel indicating an increase in engine efficiency and performance. Currently, bioethanol is produced at a large scale in several countries, including Brazil, the United States, and many European countries. Bioethanol is also projected to dominate biofuel in the sector within the next decade (Galbe et al. 2011). It can primarily be produced either in a first-generation system employing energy crops such as sugarcane and corn or in a second-generation system employing lignocellulosic-based waste. FVW is a commonly considered feedstock for bioethanol production with varying yields (Table 17.5). Madadi et al. (2021) explored bioethanol production from the saccharification of potato straw. These authors reported a maximum bioethanol yield of 24% after pretreatment in hot water for 8 min, resulting in complete enzymatic saccharification. Apple pomace was also found to be a suitable feedstock for bioethanol production when coupled with soluble soy protein. Demiray et al. (2021) reported that soluble soy protein is a cheap additive that enhances apple pomace enzymatic hydrolysis,

Table 17.6 Bioethanol production from fruit and vegetable wastes under solid-state and submerged fermentation systems

Feedstock	Fermentation system	Yield	References
Pineapple waste	Solid-state	11.3% (v/v)	Efunwoye and Oluwole (2019)
Citrus waste	Solid-state	6.0029%	Chahande et al. (2018)
Orange waste	Solid-state	32.32% (v/v)	Musa et al. (2018)
Sugar beet peels	Submerged	17.5%	Mushimiyimana and Tallapragada (2017)
Carrot peels	Submerged	16.8%	Mushimiyimana and Tallapragada (2017) and Khoshkho et al. (2021)
Onion peel	Submerged	16.97%	Mushimiyimana and Tallapragada (2017)

resulting in a sugar concentration and bioethanol concentration of 155 g/L and 52.4 g/L, respectively, employing *Saccharomyces cerevisiae* as an inoculum. Molinuevo-Salces et al. (2020) investigated apple pomace in a biorefinery scenario, where bioethanol production was conducted, followed by the subsequent biomethane production from the residues. These authors reported a maximum bioethanol and biomethane yield of 0.44 g/g and 463 mL/g VS, respectively, indicating the suitability of apple waste as a feedstock for a biorefinery system. A mixture of fruit waste, including melon, pineapple, banana, apple, and mango, was also examined as a feedstock for bioethanol production by Zanivan et al. (2021). A nonconventional yeast strain (*Wickerhamomyces* sp. UFFS-CE-3.1.2) was employed in the fermentation process, resulting in maximum ethanol productivity of 2.50 g/L/h from 36.32 g/L fermentable sugar. Vegetable waste composite, potato waste, sweet potato waste, and yam waste were also investigated for bioethanol production by Chatterjee and Mohan (2021). Following thermally assisted chemical pretreatment and enzymatic saccharification, bioethanol yields of 251.85, 240.98, 235.4, and 125.6 mg/g were obtained from sweet potato waste and yam waste potato waste and mixed vegetable waste, respectively, at 35°C with pH 5.0.

Bioethanol production has also been investigated under different fermentation systems, such as solid-state and submerged processes (Table 17.6), and it has also been reviewed in a consolidated bioprocessing (CBP) system. For instance, Efunwoye and Oluwole (2019) explored bioethanol production from pineapple waste in a solid-state fermentation system. These authors employed a co-culture of *Aspergillus niger* and *S. cerevisiae* on the substrate for saccharification and fermentation processes, respectively, and a peak bioethanol concentration of 11.3% (v/v) was reported. Chahande et al. (2018) produced bioethanol from citrus waste using baker's yeast in a solid-state and a submerged system. These authors found that the solid-state fermentation system produced the highest bioethanol yield (6.0029%). Another study employing orange waste in a solid-state fermentation system reported a bioethanol yield of 32.32 % (v/v) under optimal substrate loading, pH, temperature, and fermentation time of 200 g, 4.5, 35 C, and 72 h, respectively (Musa et al. 2018). Vegetable peel wastes, such as sugar beet, carrot, and onion, were also evaluated employing *Penicillium crustosum* in a submerged fermentation system (Mushimiyimana and Tallapragada 2017). The highest ethanol yield was observed from sugar beet peels (17.5%), followed by onion peels and carrot peels at 16.97 and 16.8 %, respectively.

Consolidated bioprocessing (CBP) is another avenue that appears viable for the large-scale production of bioethanol. In essence, CBP is a system where several processes are executed in a single step, including enzyme production, feedstock saccharification followed by fermentation by lignocellulolytic microorganisms. FVWs have also been employed in this system type. For example, Hossain et al. (2018) isolated *Wickerhamia* sp., a highly efficient amylolytic microorganism that exhibited high α-amylase and glucoamylase activity and bioethanol-producing capabilities. This microbe was employed on potato peel waste in a Plackett-Burman designed system followed by response surface optimization, which showed a high ethanol yield of 1.7 g/L. In another study, a co-culture of *Clostridium cellulovorans* and *Clostridium beijerinckii* was employed to degrade orange waste and produce bioethanol, respectively (Tomita et al. 2019). Following 45 h of fermentation, an ethanol yield of 2.5 g/L was observed.

4.4 Biobutanol from Fruit and Vegetable Wastes

Biobutanol production is most routinely produced in an ABE (acetone butanol and ethanol) system, where all three compounds are generated simultaneously. This is considered a cost-effective method to produce three value-added products from a single feedstock. Some studies examining biobutanol production from FVWs are outlined in Table 17.7. Khedkar et al. (2017) explored the production of acetone, butanol, and ethanol from cauliflower waste. These authors reported a butanol yield of 3.06 g/L after drying the cauliflower waste at 100 °C.

On the contrary, a significantly higher yield was reported from potato peel waste subjected to organosolv pretreatment (Abedini et al. 2020). This study concluded that organosolv pretreatment at 180 °C for 60 min yielded 185 g of biobutanol. However, the same feedstock exhibited a much lower yield (42 g) after dilute acid pretreatment at 180 °C for 60 min. Banana peels were also shown to be a suitable feedstock for biobutanol production, exhibiting a yield of 15.7 g/L by employing a

Table 17.7 Biobutanol yield from different fruit and vegetable waste feedstocks

Feedstock	Biobutanol yield	References
Cauliflower waste	3.06 g/L	Khedkar et al. (2017)
Potato peel waste	185 g	Abedini et al. (2020)
Banana peels	15.7 g/L	Mishra et al. (2020)

co-culture of *Saccharomyces cerevisiae* and *Pichia* sp. at 72 h of incubation time after chemical pretreatment (Mishra et al. 2020).

4.5 Biodiesel from FVW

FVWs are commonly employed as a catalyst in the production process of biodiesel. However, recent studies have been examining more "green" catalysts, as shown in Table 17.8. For example, empty palm fruit bunch waste was reacted with activated carbon and concentrated sulfuric acid at 600 C for 3 h, resulting in a catalyst of 9.0 mmol NaOH/g, ultimately yielding 50.5% fatty acid methyl ester (FAME) compounds (Wong et al. 2020). Plantain fruit peel waste was also a potential green-base catalyst in synthesizing *Azadirachta indica* oil methyl esters (AIOME). Etim et al. (2018) explored the optimization of this process employing the genetic algorithm and reported an AIOME yield of 99.2 % wt. In another study, Hussein et al. (2021) investigated the production of a sulfonated carbon catalyst using potato peels through $ZnCl_2$ activation and sulfonation. The resulting catalyst showed a high surface area of 827.7 ms/g, ultimately allowing a high conversion rate (91.2%) of oleic acid to biodiesel.

5 Microorganisms

Microorganisms vary in their ability to metabolize organic waste and their ability to produce specific products or compounds. Glucose and xylose account for the main sugars that are extracted from FVW following pretreatment and enzymatic hydrolysis. Most microbes are equipped with the basic metabolic functions to consume and convert glucose into biofuels and value-added products. This includes commonly employed yeast species such as *S. cerevisiae* for bioethanol production or bacterial species *Clostridium butyricum* for biohydrogen production (Moodley and Gueguim Kana 2019). However, xylose is not an easily metabolized sugar since most microbes do not possess the metabolic pathways to degrade it. This then limits the availability of microorganisms that can consume xylose while at the same time producing a specific product in a biorefinery system. Genetically engineered

Table 17.8 Biodiesel yield from different fruit and vegetable waste feedstocks

Feedstock	Biodiesel yield	References
Palm fruit bunch waste	50.5% FAME[a]	Wong et al. (2020)
Plantain fruit peels	99.2 % AIOME[b]	Etim et al. (2018)
Potato peels	91.2 % conversion	Hussein et al. (2021)

[a]Fatty acid methyl esters
[b]*Azadirachta indica* oil methyl esters

microorganisms have been designed and employed for this purpose. However, this avenue does present significant drawbacks. These include genetic contamination and interbreeding, competition with natural species, increased selection pressure on target and nontarget organisms, ecosystem damage, horizontal transfer of recombinant genes to other microorganisms, loss of management control measures, and several other ethical concerns (Prakash et al. 2011).

Certain microbial species, particularly those found in anaerobic sludge, possess the ability to shift their metabolic pathway when consuming different sugars. For instance, Moodley and Kana (2015) described the consumption of glucose by a mixed microbial consortium to produce biohydrogen. Once glucose depletion had been reached, the fermentation process slowed down for a few hours, after which xylose consumption began and hydrogen production continued. This phenomenon was explained as a shift in metabolism, particularly to either the phosphoketolase or pentose phosphate pathway, where xylose is further metabolized (Xia et al. 2015). Microorganisms, therefore, play a vital role in the productivity and profitability of biofuel production processes from fruit and vegetable waste. Understanding these dynamics and kinetics would allow the processes to run optimally.

6 Conclusion and Future Outlook

The production of biofuels is a constantly evolving area, with novel research and processes being developed. There have also been significant milestones that have characterized the sector and its future direction. Fruit and vegetable wastes are excellent examples of high-sugar, lignocellulosic-based waste feedstocks with the potential to produce high-yielding biofuels. However, to maximize the potential of this feedstock, an effective yet highly efficient pretreatment will play an integral role in this process. In this respect, a low-cost, highly effective pretreatment process that possesses low toxicity should be developed to enhance the process outlook significantly. In addition to this, more extensive investigations into different co-substrate ratios coupled with co-cultures to maximize glucose and xylose consumption further enhance process productivity and economic feasibility. Integrated biorefinery is another avenue that warrants more research, particularly to enhance the production of multiple biofuels from FVWs.

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Part V
Life Cycle Analysis

Chapter 18
Life Cycle Assessment of the Valorization of Fruit and Vegetable Wastes as Biocommodities and Biofuels

Noé Aguilar-Rivera and Luis Alberto Olvera-Vargas

Abstract Fruit and vegetable wastes, as renewable substrates, are composed of deteriorated, rotten, or poor products, branches, pulps, shells, leaves, seeds, etc., which are physicochemically and biologically composed of simple or structural carbohydrates such as cellulose, hemicellulose, lignin, and other compounds of interest for the food, pharmaceutical, and biotechnology industries. Hence, utilizing these renewable wastes as feedstocks would reduce the use of food commodities such as sugarcane, cereals, oilseed, and soybean in conventional processes, as well as the deforestation of tropical forests for the installation of plantations, as in the case of oil palm, all of which have a direct impact on biodiversity loss, soil deterioration, and water pollution. The elimination or transformation of these residues would work together in biorefineries and with simple or conventional technologies that are currently used for the production of livestock, organic fertilizers, biogas, and fuels such as pellets and briquettes. This research reviewed the state-of-the-art use of fruit and vegetable wastes in biorefineries evaluating sustainability issues according to the circular bioeconomy with the life cycle analysis (LCA) methodological approach.

Keywords Life cycle analysis (LCA) · Fruit and vegetable waste · Biorefineries · Biofuels · Bioproducts · Circular bioeconomy

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1 Introduction

A multitude of factors – including the restructuring of emerging economies; the growing demand for food, raw material, and energy, together with the uncertainty surrounding fossil fuels; limited access to flex-fuel, biofuels, hydrogen, and electric transportation in some regions; rising environmental pollution; and the reality of climate change's effects and its direct consequences on commodity production – have prompted developed and developing countries to seek newer, more profitable, and cleaner sources of raw materials such as crop residues, biomass, and wastes, as well as novel green processes to produce biofuels, energy, commodities, livestock, and food to maximize well-being. In this regard, fruits and vegetables are used as superfoods all over the world for their organoleptic properties, as well as their nutrients and health-promoting components. There is a wide variety and availability of species for the food agroindustry across countries, regions, and climatic zones. Because of their high quantity of dietary fiber, vitamins, and minerals, and other health boosters like antioxidants, they are consumed raw, cooked, or processed as food. They are also frozen to maintain their qualities. Various factors have led to a significant increase in the variety, availability, and nutritional quality of food, including the change in food consumption habits, with raw or partially processed, cooked, or ready-to-eat products available since the 1970s, the increase in the female labor force, migration of people from different countries due to various causes, population growth, development of production technology based on the Green Revolution, improved food preservation methods, enhanced fruit and vegetable processing, and consumer demand. Fruit and vegetable wastes (FVWs) refer to fruits, vegetables, legumes, and raw vegetables from harvest to consumption. The variety of such crops is unlimited, with each region or country concentrating on a number of them. However, among the most common are tomato, potato, corn, cereals, peas, broccoli, cauliflower, cabbage, carrot, beet, mango, pomegranate, watermelon, papaya, pineapple, jack fruit, banana, avocados, grapes, citrus, and guavas, among others. Fruits and vegetables are also an important source of agricultural waste, as are wholesale markets, retail consumption, processing industries, and homes; therefore, a huge amount of FVWs are generated, making any quantification of it complex and uncertain. The elimination of these residues in landfills can be difficult and is a significant environmental pollution concern due to their characteristic of being perishable, added to which it also increases the operating cost of the food value chain (Pattanaik et al. 2019)

Sagar et al. (2018) reviewed the production, physical characteristics, and types of residues according to each type of fruit and vegetable. They also concluded that fruit, vegetable, and byproduct losses and waste are not only constituted by the nonedible portion of these commodities, but also by the enormous quantity that is lost and wasted due to the lack of adequate operations related to production, field crop management, harvesting systems, classification, transport, storage, conservation technology (such as maintaining the appropriate temperature and relative humidity), marketing, and industry infrastructure. In addition, a noteworthy proportion of the waste is the significant amounts discarded for mainly aesthetic reasons. Thus, there is a need to use updated waste management technologies to achieve greater extraction and recovery of bioactive materials in a profitable manner.

Fruits and vegetables are commonly produced in a specific season (spring-summer, fall-winter), but, due to various factors, there may be overproduction during the agricultural year, mainly in developing countries without proper use of food preservation or handling technologies, which leads to waste. In addition, when fruits and vegetables are processed, the product demanded by the market will be obtained in fresh or processed form. The waste from the processing of fruits and vegetables such as pomace, peels, stem, stems, leaves, and seeds, among others, is estimated to be between 25% and 30% of the total (Salim et al. 2017).

However, Galanakis (2018, 2020) mentioned that the terms that should be used instead of waste are *"reutilized byproducts"* and *"wasted byproducts"*.

Afolalu et al. (2021) discussed the term wastes for fruits and vegetables and concluded that they comprise great differences in their chemical composition regarding carbohydrates, proteins, macro, and microelements; therefore, these biowastes should be called "raw materials" as the basis of a circular economy, biorefineries, or rural usage. The chemical compounds in these residues present desirable conditions as raw materials for the development of microorganisms for biotechnological processes through fermentation or thermochemical and biochemical routes, being used individually or in a mixture (as co-substrate or raw material) to promote the development of value-added products.

According to FAO (2011), about 1.3 billion tons of food per year is lost or wasted, starting at the production stage in crop fields and ending with the consumers. It is estimated that 10–20% of FVWs are generated as crop residues within the transport and post-harvest stages, and another 15–20% during industrialization and by final consumers. Fruit and vegetable production is increasing due to the demand in industrialization and consumption, as well as for their properties and health benefits, but it is also the most significant food waste contributor (Díaz et al. 2017; Vilariño et al. 2017).

Magalhães et al. (2021) identified 14 causes of food loss and waste in fruit and vegetable supply chains:

1. Inadequate demand forecasting and low level of industrialization of surplus.
2. Overproduction and excessive stocks due to few diversification strategies.
3. Poor handling and operating performance.
4. Storage at the wrong temperature or for long periods.
5. Inadequate, defective, or low protection capacity packaging system.
6. Noncompliance with regulations and retail specifications.
7. Physical, sensory, or microbial deterioration.
8. Short shelf life of the product or expired products due to inefficient harvesting or handling.
9. Effects of climate change and meteorological variability on the productivity and quality of fruits and vegetables.
10. Lack of infrastructure and storage facilities.

11. Low level of pricing strategies and management of promotions or marketing.
12. Lack of coordination and exchange of information among stakeholders.
13. Inadequate transportation systems (refrigerated).
14. Ineffective management in the store due to lack of staff training.

Concerning the above, FVWs present the most significant potential for biorefineries due to their nature and production throughout the year. However, as an initial step, a proximal analysis is needed to determine their physicochemical composition and properties, owing to their heterogeneity. Nonetheless, all these wastes have in common a high content of moisture, structural carbohydrates, lignin, organic matter, and bioactive compounds. In addition, they are a potential source of contaminants due to their high degree of early decomposition. Therefore, depending on the FVW characteristics, composition, available conversion technology, and the market demand, the most potential options are in a biorefinery (Esparza et al. 2020).

Among the potential applications for FVWs, recently the extraction of polyphenols and antioxidants from agri-food byproducts and converting these extracts into stable powders is considered of great importance for the market (Nguyen et al. 2020).

Asquer et al. (2013) carried out a detailed study of the chemical and physical properties of representative fruit and vegetable wastes disposed of by a wholesale market in Italy. They found that fruit residues have higher total solids, volatile solids, and C/N ratios than vegetable wastes. Total solid content in fruits was within the 7.5–23% range on a wet basis and 3–11% in vegetables. Volatile solid content in fruits was in the range of 5–12%, and 2–9% in vegetables. Finally, the C/N ratio of the fruit wastes (19–53%) was also significantly higher than that of vegetables (10–21%).

Additionally, FVWs can be industrialized to obtain bioactive compounds, functional foods, biochar, biosorbents, cosmetics, terpenic compounds, dietary fiber, gallic acid, polyphenols, textiles, pharmaceutical industry applications, dietetic fibers, edible coatings, and synthesis of carbon dots (CDs), as a new type of carbon-based nanomaterial. Moreover, FVWs contain cellulose, fermentable sugars, hemicellulose, and starch.

For Lucarini et al. (2020), *the "Universal Recovery Strategy for the commercial recovery of valuable compounds from food wastes mainly FVWs represents a new goal of the circular bioeconomy and the biorefinery concept: waste is recycled inside the whole food value chain from field to fork and represents a sustainable alternative source of biologically active compounds to formulate functional foods and nutraceuticals."*

The development of sustainable FVW management has become extremely important due to the impacts of climate change resulting from various sources such as conventional agriculture, and which is expected to create difficulties for worldwide food production. On the other hand, increasing obesity and related diseases are attributed to a low daily intake of fruits and vegetables.

Therefore, current fruit and vegetable production requires novel technological options that could exploit the composition and overabundance of FVWs and support sustainability from these foods and producing regions, thereby minimizing waste and generating well-being. At the same time, FVWs are a potential source of carotenoids, phenolics, vitamins, enzymes, and essential oils, which could together serve as an economic driver for a biorefinery.

2 Biorefinery of Fruit and Vegetable Wastes

A biorefinery is a novel and emerging technology that reuses biowastes and byproducts, and converts biomass and its residues through the technological, administrative, and energetic integration of several conversion routes to various bioproducts such as biofuels, biochemicals, and biopolymers, considering different economic contexts and potential end products (Kumar et al. 2020a, b). In contrast, conventional technologies based on combining factors of production (facilities, supplies, work, knowledge) essentially follow an "end-of-pipe" approach, meaning that they aim to minimize the impacts and damages caused to human health, populations, and the environment and finally disposing of the wastes already generated with a technological solution such as a wastewater treatment plant or a landfill (Esparza et al. 2020).

A biorefinery is based on the principle of zero waste generation and produces high value-added bioproducts from residues, wastes, and byproducts. The process selection, technology, feedstock, and size of the biorefinery are entirely dependent on targeted end-bioproducts (Ramesh et al. 2021). A biorefinery, as a green technology, can be classified into three types (I, II, and III) based on biomass sources, targeted bioproducts, and bioprocesses or combined with chemical or conventional ones.

- A Phase I biorefinery has almost no flexibility during the whole process; it typically uses one type of biomass source, one process (generally physicochemical), and one targeted product (production of sugar or ethanol from cane) with minimal or no waste utilization.
- A Phase II biorefinery, by virtue of implementing technological modifications, can produce a lot of products from biomass during the process (bioelectricity, bioethanol, and sugar).
- A Phase III biorefinery is more complex and flexible than a Phase II biorefinery. It can produce multiple value-added products and use different types of feedstocks (lignocellulose, algal biomass, municipal solid waste, agro-industrial waste) and processing methods (physical, chemical, physicochemical, and biological pretreatments). This is very important for the integrated processing of food waste, with different types of waste and characteristics whose supply is usually highly seasonal (Jin et al. 2018).

The economic feasibility of a biorefinery is based on the production of high-value products at various technological levels or generations; for example, fruit and vegetable waste is based on a framework as a waste hierarchy (Fig. 18.1).

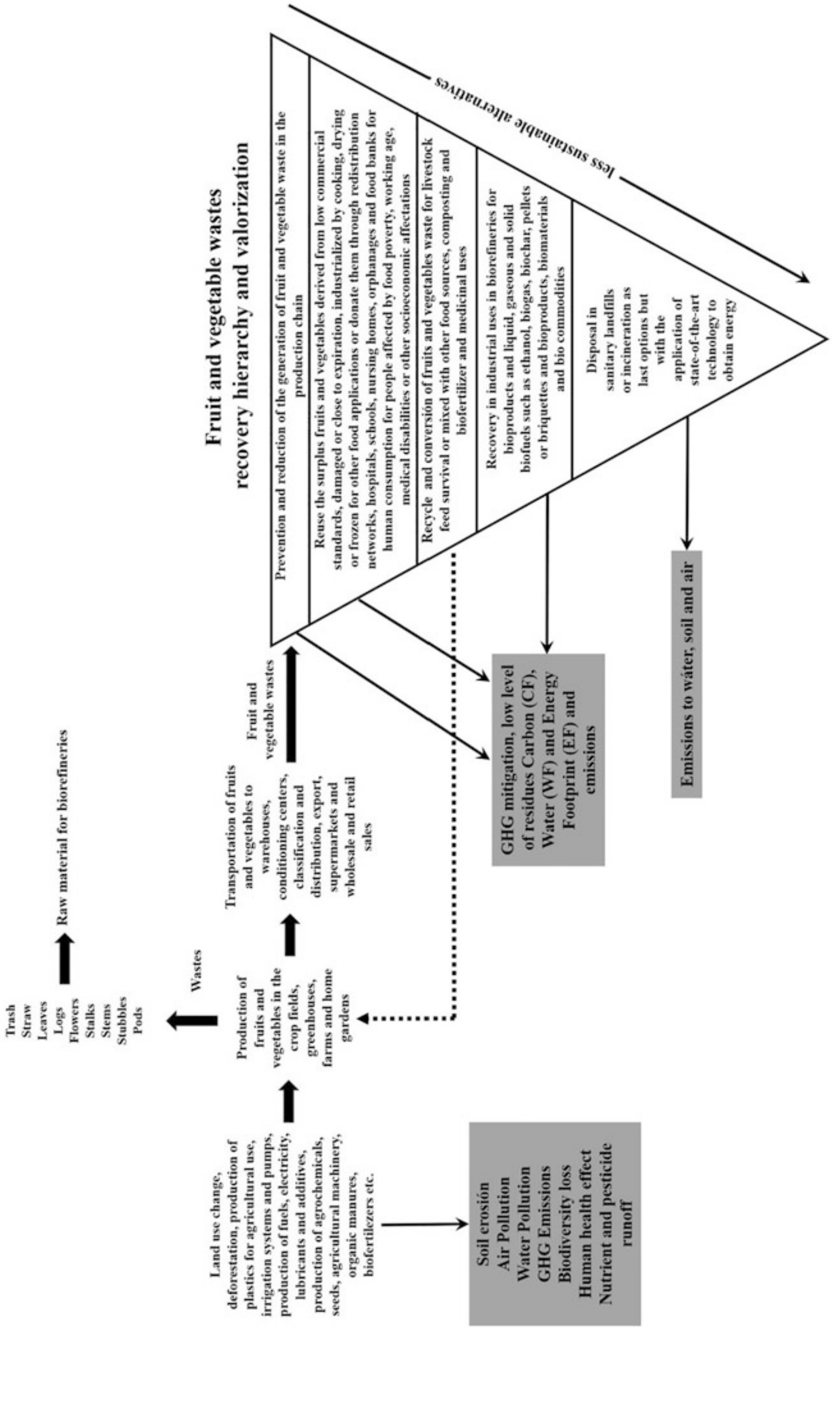

Fig. 18.1 Fruit and vegetable waste recovery hierarchy and valorization

For Rodríguez-Valderrama et al. (2020), *"the biorefineries are outlined by the following sections: (i) pretreatment to fractionate biomass, (ii) bioprocesses or combined process (iii) purification of bioproducts to discard impurities and pollutants to a new process, and (iv) energy conversion from waste."*

The first phase is based on the direct conversion of raw materials as different FVWs at low processing levels at farms, warehouses, distribution centers, food processing factories, supermarkets, or landfills.

The second step refers to the integration of productions based on wastes and intermediate bioproducts of little complexity leading to end products with special characteristics and applications.

The third step refers to processes made by physical, chemical, biochemical, and biotechnological changes using fruit and vegetables and byproducts as raw materials. The final properties of products are completely different from those of the original raw materials. The technologies are characterized by medium to high complexity.

The fourth step generates products derived from the second and third stages; they are promoters or intermediaries for other processes. They are generated through the combined use of complex chemical, biotechnological, biochemical, and mixed technologies. The final products have a high added value in the market.

However, the increasing worldwide generation of organic wastes (food, agroindustrial byproducts, lignocellulosic biomass, energetic crops, and municipal waste) has led to an overestimation of the economic attractiveness of their processing in biorefineries in several regions of the world, mainly due to the numerous constraints on the use of these wastes as feedstocks or substrates, such as their recalcitrant nature and seasonal availability, as well as the fact that several technological challenges remain to be overcome in relation to the pretreatment methods required for their processing, thereby hindering their large-scale use. Therefore, it has been proposed by several kinds of research that the combination of multiple sources of biomass and waste available during the agricultural year, or agroindustrial residues, would be a feasible technological option to improve bioproduct yields and reduce production costs.

However, utilization of FVWs in a biorefinery is still in the initial stages and lacks technological advances. Findings and developments are still focused on utilizing some particular fruit or vegetable (tomato, citruses, grape, olive, etc.). Hence, there is a great need for researchers and decision-makers to work together to sustainably exploit the technological potential of these wastes with the support of initial investment by stakeholders, and to contribute towards the reduction of the environmental impact of agriculture, agroindustry, and municipal wastes (Kumar et al. 2020a, b).

The review of Panda et al. (2018) focuses on high value-end biocommodities produced with the microbial processing of fruit and vegetable wastes, such as fermented beverages, single-cell proteins, single-cell oils, biocolors, flavors, fragrances, polysaccharides, biopesticides, plant growth regulators, bioethanol, biogas, and biohydrogen.

Devi et al. (2020) analyzed nonconventional extraction techniques (such as pulsed electric fields, ultrasounds, microwave-assisted extractions, sub-, and supercritical fluid extractions) and solid-state fermentation recovery of specialty biochemicals and nutraceutical compounds.

Ubando et al. (2020) concluded that two available technologies could be the starting point for establishing biowaste valorization: anaerobic digestion and pyrolysis. Subsequently, they may be incorporated to extract dietary fibers with high market value and di- and mono-oligosaccharides containing pre-biotic nondigestible characteristics, antioxidants, and vitamins.

Chakravarty and Mandavgane (2021) reported that biogas is generated during the anaerobic digestion of FVWs where the biofuel (biogas) and biofertilizer production is a potential solution to pollution and soil degradation, closing the cycle within the value chain in addition to generating an economic benefit. However, there is still the absence of adequate public environmental and renewable energy policies in many regions worldwide that would allow changing stakeholders' attitudes that currently lead to irrational and informal FVW disposal practices.

3 Life Cycle Assessment (LCA) of a Fruit and Vegetable Biorefinery

According to Joglekar et al. (2019), fruit and vegetable production generates a significant amount of waste that comes from plantations, crop fields, greenhouses, and home gardens, among other sources, during handling, harvesting, postharvesting, processing, packing, distribution to the final domestic consumer and export operations. Therefore, it is a value chain that generates in each link numerous wastes and environmental impacts, since most of these wastes are disposed of in landfills, clandestine garbage dumps, vacant lots or in bodies of water without treatment, etc. These cause environmental pollution because, as a whole, FVW is a very complex waste and varies depending on the region, season, lifestyle, and eating habits of the population, and is challenging to handle, reuse and reconvert due to its high moisture and biodegradability.

Instead of recovering and reusing FVWs for traditional uses such as conventional medicine, organic manures, and survival livestock feed, and by means of basic technologies such as biogas production in farms or distribution centers for a unique production, it would be sustainable to develop an integrated framework for several flexible applications that would assure the profitability of converting entire biomass or waste into bioproducts (Table 18.1).

Li et al. (2020) described the development of profitable, low pollution, cost, and maintenance facilities for improving the utilization level of wastes. Moreover, biological waste utilization as a sustainable renewable feedstock is a socioeconomic option to replace fossil sources for the production of biochemicals, biomaterials, biomolecules, and liquid, solid, and gaseous biofuels with a remarkable reduction of CO_2.

Table 18.1 Frameworks for management of the largest fruit and vegetable crops in the world and wastes

Topic	Conclusions	Reference
Fruit and vegetable integrated biorefinery	Waste biorefinery is a novel approach for the valorization of food waste. The efficiency of the end bioproducts and the cost of production are the main issues that need to be resolved to realize the integration of food waste into the bioeconomy.	Tsegaye et al. (2021)
Fruit and vegetable biorefineries	The utilization of food waste as biorefinery feedstock is a sustainable option to conventional waste management methods and contributes to reducing the amount of disposal residues, offering the opportunity to improve the economic and environmental performance of the food sector.	Moreno et al. (2021)
Food waste biorefinery	Integrated processing of food waste with a combination of different novel technologies to produce multiple products based on a biorefinery has significant advantages, including full utilization of feedstocks, minimization of waste generation during processing, synergy effects of different technologies, and diversification of revenues by covering multiple markets.	Jin et al. (2018)
Tomato	Tomato processing produces a considerable amount of waste composed of peel, seed, and pulp. Usually, they are disposed in landfills and only partially reused by composting or drying for animal feeding. Modern eco-compatible technologies offer more efficient strategies as a sustainable means for the extraction of value-added chemicals, such as carotenoids, ascorbic acid, tocopherols, and polyphenols.	Grassino et al. (2020)
Blueberry crop residues (BCR)	Applications as feedstock in a bioprocess for obtaining a range of value-added products, in order to offer economic viability, business development and market potential, and future prospects.	Liu et al. (2021)
Potato peels	Potato (*Solanum tuberosum* L.) is the most important vegetable crop; the sustainable valorization of byproducts presents great interest for the food and pharmaceutical industries that could increase the overall added value.	Sampaio et al. (2020)
Citrus fruits	Friendly valorization strategies for the effective reuse and recycling of citrus byproducts are reviewed in order to establish strategies to reduce the environmental impact as well as to meet the increasing demand of society for functional foods, fuels, and energy.	Panwar et al. (2021)
Apple	Development of value-added routes of apple pomace towards production of bio-chemicals is characterized by lack of holistic research. Integrated approach with techno-economic analysis, life-cycle assessment, and inter-sectorial initiatives will possibly reveal the most promising valorization routes.	Awasthi et al. (2021)
Grape	The winemaking sector is one of the most productive worldwide, and thus it also generates large amounts of	Troilo et al. (2021)

(continued)

Table 18.1 (continued)

Topic	Conclusions	Reference
	byproducts (vine shoots, grape stalks, wine lees, grape pomace, grape seeds, grape stalks, and wine lees) with high environmental impacts. The review shows the potential to be recycled into the food chain as functional additives for different products and applications, supporting the sustainability of the winemaking sector.	
Bioactive compounds from FVWs	The review reports an updated survey of different bioactive compounds FVWs utilizing biorefinery techniques for their extraction for bioenergy production and the various extraction techniques of the bioactive compounds.	Sengupta et al. (2020)
Valorization of FVWs	The current valorization trends of byproducts obtained in different food industries, particularly those generated during processing of cereals, coffee, meat, olives, grapes, and other fruits, is a flexible production method in biorefineries.	Galanakis (2020)

The generation of high-value bioproducts and the integration of multiple technologies in a biorefinery that uses waste and byproducts close the gap between technology and the market. However, a critical analysis of environmental sustainability is required through life cycle assessment (LCA), process integration, and optimization (Ubando et al. 2020).

However, LCA approaches typically account for the environmental impacts of greenhouse gas emissions or carbon footprint, water consumption, land, chemical, and energy use, effects of pollution and anthropic activities, and biodiversity loss.

Bio-based products (biofuel, bioplastics, bioenergy, fibers, etc.) are also vulnerable to potential environmental drawbacks resulting from the use of certain crops such as sugar cane, corn, soybeans, cassava, cereals, rapeseed, oilseeds, etc. that have been used by the food and agriculture sector since ancient times, and their diversion to biorefineries could increase land use, deforestation, energy consumption, fossil fuel use for transportation, etc.. In addition, indirect emissions by auxiliary processing facilities or construction, conventional or green inputs, additional water, and chemicals for processing in a biorefinery impact the environment. Therefore, the sustainability (ecological, economic, and social) and impacts resulting from inputs and outputs and the various technological processing steps in a FVW biorefinery or biofactory should be evaluated during the initial design phase using tools like LCA to transition to sustainable processes.

Another aspect to consider is the high perishability of fruits and vegetables. Their handling and disposal are quite censorious to community acceptance since they contain very high moisture contents and rot and degrade easily. To ensure good conversion efficiencies and process stability in biorefineries, it is imperative to precisely characterize the physical and chemical properties of the waste, such as the total solid, volatile solid, carbon, nitrogen, macro-, micro-, and trace- elements contents (Asquer et al. 2013).

Based on current or available technology, irregular supply of primary biomass during the agricultural year of specific crops and generated waste, their processing and generation of byproducts or coproducts, and considering the market demand against established products derived from oil, wood, minerals, cereals, etc., a more generalized biofactory can be designed, focusing on several bioproducts. Moreover, at the design stage, it is necessary to identify environmental impacts. The use of LCA as a tool helps in identifying strategic points of the environmental impact of the process to improve with FVWs as raw material because the use of novel and advanced technologies is critical to minimize environmental impacts (Fig. 18.2).

4 Industrial Application: Cellulose for Paper and Cardboard from Banana and Pineapple Waste

Numerous non-wood materials such as sugarcane bagasse, straw from various cereals, rice, wheat, maize, barley, bamboo, kenaf, abaca, sisal, and others are lignocellulosic waste from some agro-industrial processes marginally used as biomass for the production of energy (electrical, mechanical and steam) and in the pulp and paper industry as a source of cellulose (Mboowa 2021; Abd El-Sayed et al. 2020; Laftah et al. 2016) mainly in developing countries. However, several wastes could potentially be a source of cellulose for paper and cardboard, derivatives of cellulose, and bioproducts with a very high value-added. Otherwise, the nonedible parts of fruits and vegetables after harvest, processing, or consumption constitute around 10–60% of the product's total weight and are composed of peel, skin, husk, seeds, sheaths, pulps, and other parts of the plant of origin such as leaves, branches, trunks, roots, etc. For example, the production of fruits such as pineapple and banana, which are widely cultivated in tropical countries such as Mexico, generate a large amount of harvesting and handling residues such as pineapple crown leaves and banana pseudo-stems (Figs. 18.3 and 18.4), which represent 29.3% and 38.3% of the plant, respectively (Gutierrez 2018). These wastes are characterized by a good amount of cellulose and low hemicellulose and moderate lignin contents. Their fiber length is medium to long, with high availability for conventional pulping processes such as soda, soda-anthraquinone (AQ), obtaining a kappa (residual lignin) number below 20, making it an easily bleachable pulp. Therefore, these wastes shown excellent properties for papermaking (Mboowa 2021).

4.1 *Pulping Banana Stem and Pineapple Crown Leaves*

The delignification by the soda (NaOH) process of banana stem chips and pineapple crown leaves was evaluated according to the methodology and conclusions of Balda et al. (2021); Ferdous et al. (2021); Tripathi et al. (2019); Praveen (2020) and Prado

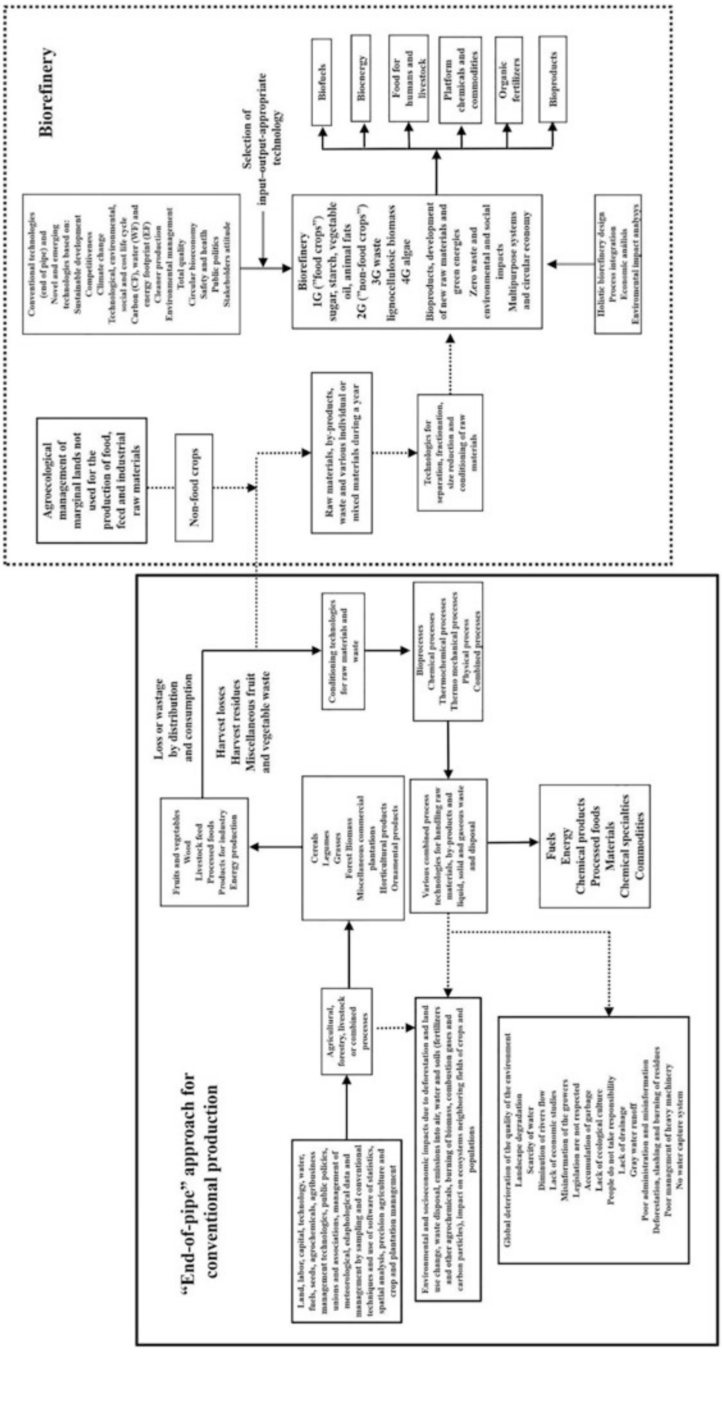

Fig. 18.2 Management of waste and byproducts in a conventional end-of-pipe approach and biorefinery

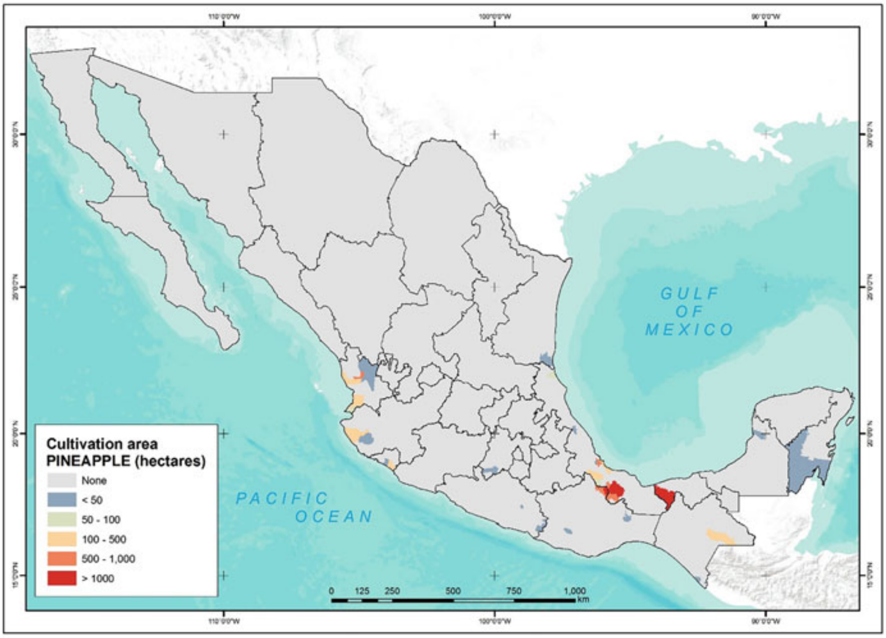

Fig. 18.3 Pineapple production. (Data from SIAP, 2019 https://nube.siap.gob.mx/avance_agricola/)

et al. (2020). Banana pseudo-stems presented an initial moisture content of 83.3% when cut from a plantation, and pineapple crown leaves had 72.5% when collected from a local market. Both materials were dried directly in the sun to reduce moisture to 18.4% (Fig. 18.5).

Both residues were delignified separately in an isothermal batch reactor (digester) with 8.75% alkali (as Na_2O based on OD weight of pulp), hydromodule 5:1, temperature 165 ° C, and pressure of 5 kg/cm for 20 min of reaction, obtaining a yield of cellulose pulp for banana stem chips of 32.7% and pineapple crown leaves of 39%. The physical properties were determined according to TAPPI (Technical Association of Pulp and Paper Industry) standards (Table 18.2).

4.2 *Elemental Chlorine-Free (ECF) Bleaching*

The brown pulps obtained were bleached using the conventional ECF (elemental chlorine-free), HEP (delignification with NaClO- alkaline extraction with NaOH - bleaching with peroxide H_2O_2) sequence. The operating conditions were established based on the residual lignin content according to the kappa number (7.4 for banana stem and 9.0 for pineapple crown leaf pulps) to obtain an ISO brightness of at least

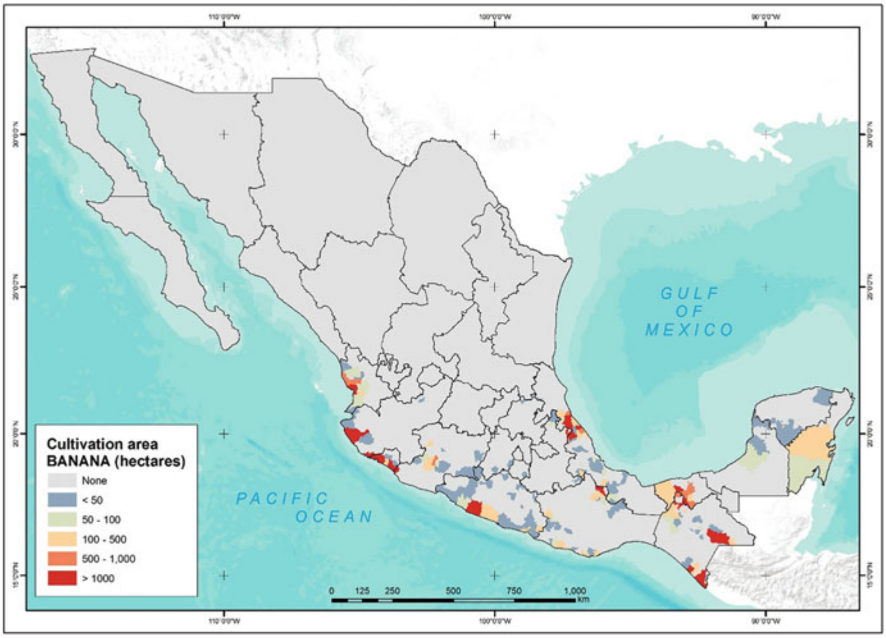

Fig. 18.4 Banana production. (Data from SIAP, 2019 https://nube.siap.gob.mx/avance_agricola/)

Fig. 18.5 Pineapple and banana wastes. (Photographs taken in Veracruz, Mexico)

75% for high-quality pulps. In addition, evaluation of mechanical resistance and drainage characteristics was carried out on both pulps (Tables 18.3 and 18.4).

4.3 Paper Production

Premier grade paper of high resistance as Kraft paper of 130 gm^{-2} base weight was successfully manufactured in the stock preparation stage (mixture of refined pulps and sizing) according to the TAPPI test by substituting softwood pulp and recycled Old Corrugated Container (OCC) pulp with banana stem and crown pineapple leaf

Table 18.2 TAPPI test used to determine the physical properties of banana stem pulp and pineapple crown leaves (TAPPI 2000)

Kappa number of pulp	T 236 cm-85.
Forming handsheets for physical tests of pulp	T 205 sp-02
Laboratory beating of pulp (Valley beater method)	TAPPI/ANSI T 200 sp-15
Bursting strength of paper	T 403 OM-15
Internal tearing resistance of paper (Elmendorf-type method)	T-414 om - 88
Brightness of pulp, paper, and paperboard (directional reflectance at 457 nm)	TAPPI/ANSI T 452 om-18
Folding endurance of paper (Schopper type tester)	T 423 cm-07
Refining level (*Schopper-Riegler* method)	SCAN-m3:65
Freeness of pulp (Canadian standard method)	T 227 om-17
Water absorptiveness of sized (non-bibulous) paper, paperboard, and corrugated fiberboard (Cobb test)	TAPPI T 441

Table 18.3 Mechanical resistance of banana and pineapple cellulosic pulps

Unbleached pulps		
Pulp Mechanical resistance	Soda pulp of banana stem	Pineapple crown soda pulp
Tear (mN)	2495	1587
Burst (kgcm^{-2})	3.056	2.162
Folding endurance (double folds)	1834	74
Bleached pulps		
Pulp Mechanical resistance	Soda pulp of banana stem	Pineapple crown soda pulp
Tear (mN)	1849	680
Burst (kgcm^{-2})	2.782	1.899
Folding endurance (double folds)	919	12
Brightness (%)	76	77

Table 18.4 Beating and mechanical resistance of banana and pineapple waste pulps

Pulp	Beating time (minutes)	Refining level (°*SR*)	Freeness of pulp (mL CSF)	Tear factor	Burst factor	Folding endurance
Unbleached banana stem	0	14.5	713	282.76	33.95	1834
	25	33.3	384	254.55	39.74	5063
Unbleached crown pineapple leaves	0	60	147	184.91	10.01	74
	5	65.6	112	139.7	24.13	142
Bleached banana stem	0	17.3	643	156.31	23.93	919
	15	41.7	286	136.57	41.07	3607
Bleached crown pineapple leaves	0	62	123	69.36	15.83	12
	5	68	105	77.68	26.48	53

Table 18.5 Classification of paper from banana and pineapple pulps and old corrugated container (OCC)

Type of paper (pulp composition %)	Banana stem	Crown pineapple leaves	Old corrugated container	°COBB (degree of sizing)
A	100			18.54
B		100		14.73
C	50	50		15.26
D	50		50	16.9
E		50	50	14.06
F	25		75	17.3
G	25	25	50	13.47
OCC paper	Mainly OCC waste			16.31
Semikraft paper	Mainly virgin semi-chemical fibers			18.98
Kraft paper	Mainly virgin semi-chemical fibers			17.06

Table 18.6 Mechanical resistance of banana and pineapple paper

Type of paper (Pulp Composition %)	Tear factor	Burst factor	Folding endurance
A	256.47	43.88	5693
B	187.94	24.52	157
C	205.85	32.78	2574
D	235.06	34.06	2091
E	173.28	25.72	365
F	231.45	28.55	1647
G	178.07	29.70	2786
OCC paper	141.78	23.15	97
Semi Kraft paper	171.36	27.42	429
Kraft paper	234.6	44.27	2831

pulp without any adverse effect on the physical strength properties of the paper (Tables 18.5 and 18.6)

The waste utilization of banana stem and pineapple crown leaves as a raw material for papermaking will be valuable for the sustainable growth of the paper industry, because both pulps have resistance properties equivalent to products derived from commercial wood-based processes as raw material. In addition, the bleached pulp can be used in the paper industry as a partial or total substitute for commercial pulps by using other bleaching sequences such as the elemental chlorine-free or chlorine-free ones (to obtain cellulose derivatives or other bioproducts).

4.4 Use of Bio-Dried Waste as an Additional Fuel in Farm and Industrial Boilers

Solid and liquid agro-industrial wastes have a high biological oxygen demand (BOD) and chemical oxygen demand (COD). Also due to their physicochemical composition, they are highly susceptible to aerobic degradation due to bacterial contamination resulting from their high moisture content. Therefore, their final disposition is technologically very complex. However, these agro-industrial wastes are high in cellulose, lignin, hemicelluloses, sugars, fibers, proteins, and minerals. Due to their composition, there is currently great interest in their reuse as raw materials for biorefineries (Ritota and Manzi 2019).

Bio-drying is a mechanical-biological process that works with the biodegradability of any waste by removing moisture from biodegradable material and thus transforming it into an alternative solid fuel for energy purposes. It uses the heat released during the degradation of waste to reduce the moisture and partially stabilize the biomass, lower CH_4, CO_2, SO_2, and NOx emissions (mitigation of global warming for disposal), decrease waste mass, and reduce odor and dust emission from waste landfills into the atmosphere (Mohammed et al. 2018; Avelar et al. 2019). Therefore, bio-drying aims to modify the waste's characteristics to increase its low heating value due to moisture (Yang et al. 2017; Tom et al. 2016).

Dos Reis et al. (2019), Ab Jalil et al. (2016), and Cai et al. (2012) found that by using forced aeration in bio-drying piles employing wet wastes and a structuring agent, 62% of total water removal takes place during the first thermophilic phase. The authors also found that this process for wastes creates pores and a layered structure with smooth edges, favoring the degradation of aromatic proteins, which are soluble microbial byproducts. Consequently, the thermophilic phase is the most critical in transforming bound water into free water, which can be evaporated during the process. Therefore, bio-drying is performed aerobically, in which the convective evaporation process is used to reduce the water content in the substrate, with minimal aerobic degradation (Velis et al. 2009).

Ham et al. (2020) concluded that temperature is critical in bio-drying since an increase in the pile's air temperature results in greater water removal from the substrate. In the particular case of the significant volume of waste produced by the citrus agroindustry of Mexico, plant species belonging to the family Rutaceae, such as orange, mandarin, lime, lemon, sour orange, and grapefruit, among others, are fruits with beneficial nutrients for human beings and are highly consumed worldwide (Figs. 18.6 and 18.7). Furthermore, the processing of citrus byproducts potentially represents a rich source of antioxidants, phenolic compounds, and dietary fiber. However, these fruits produce a large amount of peel as waste, which alone accounts for almost 50% of the wet fruit mass. Failure to process this material implies significant economic losses, particularly in the case of oranges. Accordingly, the huge volume of waste generated during juice and pulp extraction has led to increased interest in using this waste in the green process for bioproducts (Mariana et al. 2021; Jiménez-Castro et al. 2020; Siles et al. 2016).

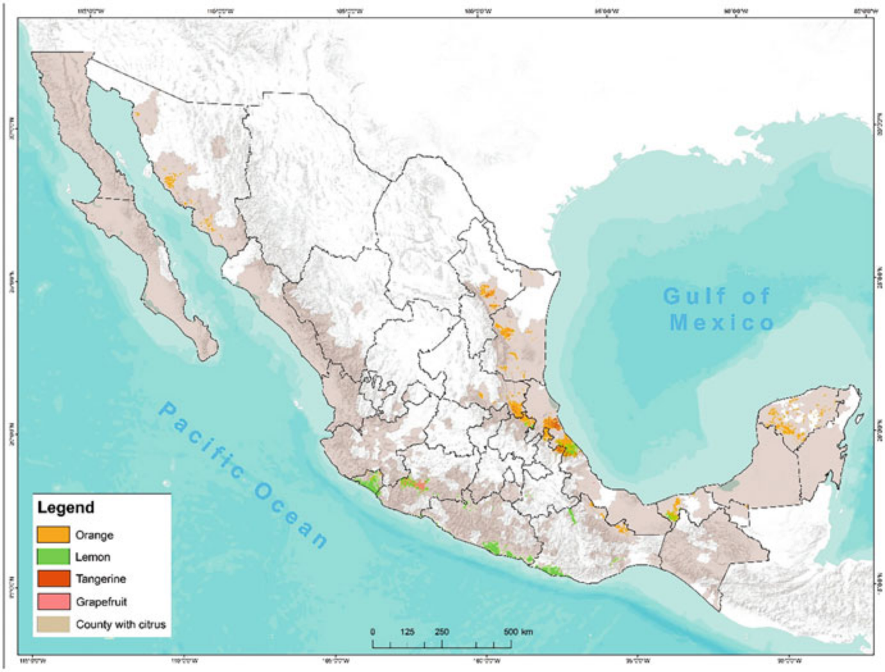

Fig. 18.6 Orange (*Citrus sinensis* (L.) Osbeck) production in Mexico. (Data from SIAP, 2019 https://nube.siap.gob.mx/avance_agricola/)

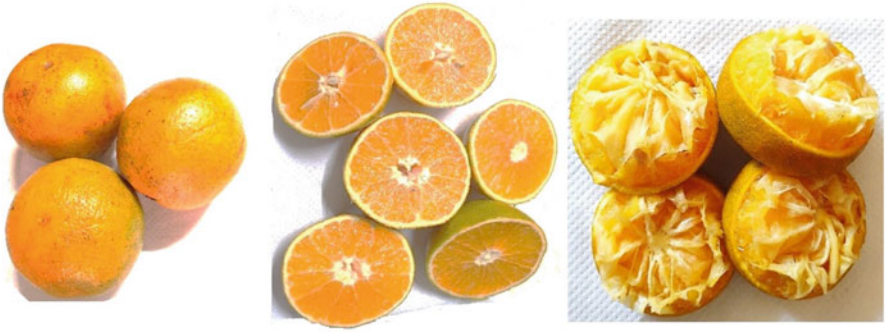

Fig. 18.7 Orange citrus fruit and waste. (Photographs taken in Veracruz, Mexico)

Sugarcane leaves from trash, whole bagasse (fiber and pith) from sugar mills, and mulch were used as structuring materials to favor forming a porous matrix inside the pile that allowed airflow and accelerated degradation (Ham et al. 2020). At the farm level, two static biodrying piles with orange peel, mulch, trash, and sugarcane bagasse as substrates, and a rectangular pyramidal structure were used. Besides maintaining the aeration process in the substrates, a forced aeration system was

Table 18.7 Composition of bio-drying pile

Raw Material	Kg	%	Moisture (%)
Orange peel	80	26.14	84.4
Forest waste	88	28.76	28.3
Sugarcane trash	90	29.41	56.8
Bagasse	48	15.69	26.5
Volume		1.3093 m^3	
Weight		306.0 kg	
Height		1 m	

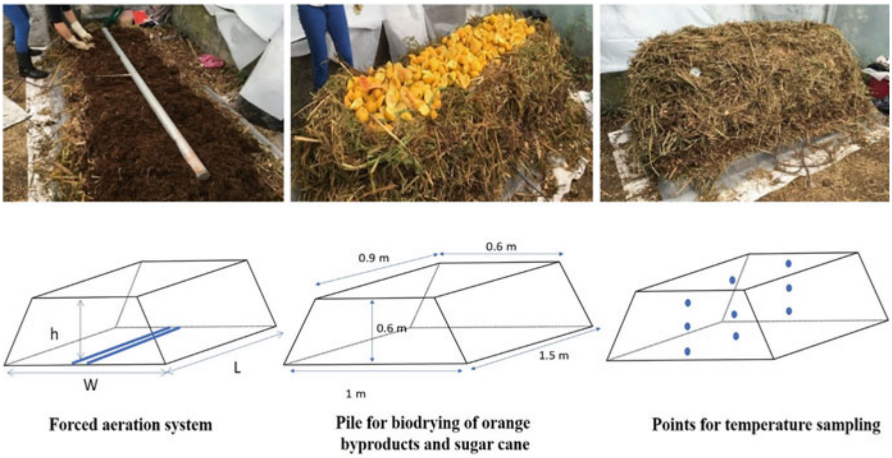

Fig. 18.8 Biodrying stages of orange and sugarcane byproducts

used, providing a volume of 25 L/min. The aeration process was performed every 2 h with a volume of 125 L/min (Aguilar-Rivera and de Jesús Debernardi-Vázquez 2018).

The piles were formed with a pyramidal arrangement with a major base of 1.0 m × 1.50 m, a height of 0.6 m, and a minor base of 0.6 m × 0.9 m. This structure was maintained during the turnings made weekly to promote the aeration process and the mixing of materials. Additionally, the temperature of the air entering the pile through the forced ventilation system can cause the hydration of the substrate or water loss as a result of the gas exchange that occurs on the surface of the materials (Table 18.7 and Fig. 18.8).

In the bio-drying piles, four phases are carried out in the evolution of the temperature: (1) initiation, (2) thermophilic, (3) second heating, and (4) decay (Cai et al. 2012); this is because when the substrates of the pile are turned, the inner section is homogenized and the concentration of oxygen, available water, and nutrients for the microbial activity are changed.

During the research process, it was observed that the temperature inside the piles remains in the range of 55–60 °C for a more extended period. This phenomenon is because, in the center of the piles, there is a condensation of water that is evaporated

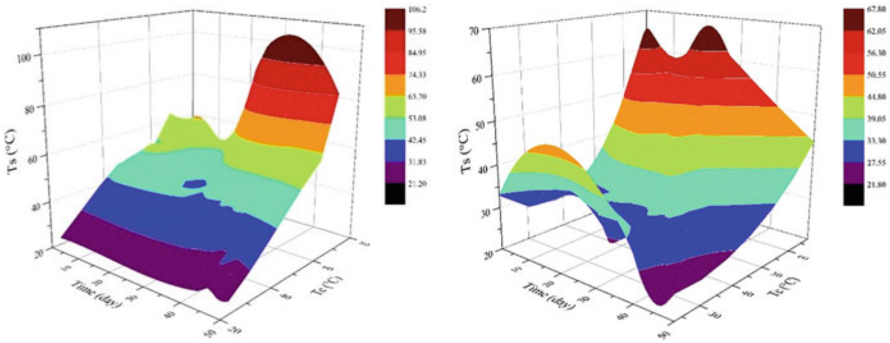

Fig. 18.9 Contour plot for the bio-drying stack

and released from the materials processed. Because they are not homogenized by employing periodic turning, the microbial activity remains in the thermophilic phase for a longer time (65 days). This effect necessitates combining the forced aeration process with periodic turnings to ensure a good bio-drying of the materials and avoid excessive degradation of the substrate in some regions of the pile if this is intended to be used as a fuel. The behavior of the temperature in the bio-drying pile had a uniform distribution which is observed in the central layer of the piles, with temperatures ranging from 23 ° C to 69 ° C, which was the maximum value reached in this layer concerning bio-drying time in days (Fig. 18.9).

The figures 18.9 show that the optimal temperature for the process was 85 °C; however, in the actual process, the maximum temperature reached was 69 °C. It was concluded that during the experimental process, variations do not affect the ambient temperature of the thermophilic phase evolution in the center of the pile since the material present in the surface thereof provides the insulating or thermoregulatory process function. For pile 2, the optimum temperature for the process was 68 °C, while in the actual process, the maximum recorded was 63 °C during the thermophilic phase. It was seen that in both piles the material on the surface contributes to maintaining moisture inside the cell, which favors the growth of microorganisms. In addition, the turning of pile materials allows gas exchange and facilitates the bio-drying process.

Biodrying as a rural process should be carried out in short periods, because the substrate is degraded as little as possible and the resulting solid biofuel maintains its calorific value incinerated or stored as rural biofuel or can be sold for energy cogeneration. As a consequence of the dehydration process by bio-drying of the pile substrates, an average moisture decrease of 87.72% was obtained for the bio-drying pile. In addition, the process considerably favored their volume reduction (73%), directly impacting transportation and final disposal costs, thereby positioning this process as a sustainable option for the treatment of solid wastes with high moisture content, since it requires low energy consumption and the water used throughout the process comes from the substrate used. Table 18.8 presents the

Table 18.8 Chemical composition of biodried biofuel from orange and sugarcane waste

Variable	Unit	Value
Moisture	%	12.295
pH	–	4.915
Soil electrical conductivity	dS/m	1.45
Ash	%	5.72
Organic matter	%	93.22
Total carbon C	%	53.32
Total nitrogen N	%	1.16
C/N	–	46
Ca	%	1.592
Mg	%	0.193
K_2O	%	0.952
P_2O_5	%	0.2865
Microelements	%	0.145.945

results of the analysis of solid biofuel according to Mexican standard NOM-021-SEMARNAT-2000 (Table 18.8).

The solid biofuel obtained had 12.3% moisture, pH 4.92, 5.72% ash, and 93.2% organic matter. In this type of biofuel, ash content can be a significant constraint on its rural or industrial use, so it should be low. In relation to the nitrogen content of 1.16% and carbon of 53.3% with a C/N ratio of 46, the latter value is desirable for this type of biomass-derived biofuel as it favors low NOx formation (Zhang et al. 2018; Yang et al. 2017).

5 Conclusions

With the rise of green businesses and biorefineries, stakeholders must evaluate a set of environmental, social, productive, technological, institutional, political, and economic factors related to the availability of raw materials and their processing. Fruit and vegetable wastes are byproducts of a basic agro-industry system and can therefore work in a complementary and cumulative manner as a way to leverage factors or constraints derived from the sustainability of agro-industrial waste uses in new value chains. In the present analysis, case studies of pulp and paper production and solid biofuel are presented as an example of the beneficial effects of conventional technologies transforming food waste into bioproducts with the sustainability approach in the transition to biorefineries. FVWs have great potential for the development of biorefineries, which is demonstrated through the analysis of the literature, which establishes that the increase in productivity, the expansion of the production of agro-industrial crops, and the technological management of waste and byproducts with the sustainable approach and assessment frameworks such as LCA are vital points. On the other hand, the adoption of green technologies and the use of FVWs in the production of bioproducts is also a function of qualitative factors of the stakeholders such as age, education, producers' debts, size and type of productive unit, economic scale, type of existing crops, inputs (labor, fuels, fertilizers, herbicides, seeds, machinery), and the target market (local, regional, national, export). These are limiting factors that must be evaluated in a systemic and multidisciplinary way in future biorefinery projects.

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