CHAPTER 3

Processing of Food Wastes

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Abstract Every year almost 45 billion kg of fresh vegetables, fruits, milk, and grain products is lost to waste in the United States. According to the EPA, the disposal of this costs approximately $1 billion. In the United Kingdom, 20 million ton of food waste is produced annually. Every tonne of food waste means 4.5 ton of CO_2 emissions. The food wastes are generated largely by the fruit-and-vegetable/olive oil, fermentation, dairy, meat, and seafood industries. The aim of this chapter is to emphasize existing trends in the food waste processing technologies during the last 15 years. The chapter consists of three major parts, which distinguish recovery of added-value products (the upgrading concept), the food waste treatment technologies as well as the food chain management for sustainable food system development. The aim of the final part is to summarize recent research on user-oriented innovation in the food sector, emphasizing on circular structure of a sustainable economy.

I. INTRODUCTION

A. Food industry wastes: Problems and opportunities

Official surveys indicate that every year more than 160 billion kg of edible food is available for human consumption in the United States. Of that total, nearly 30% (45 billion kg)—including fresh vegetables, fruits, milk, and grain products—is lost to waste by retailers, restaurants, and consumers (Rizvi, 2004). It costs the United States around $1 billion every year just to dispose of all its food waste, according to the EPA. Proportionately, the United Kingdom and Japan have traditionally been among the worst offenders worldwide in recent years when it comes to food waste, discarding between 30% and 40% of their food produce annually. The headline figures suggest that 6.7 million ton of household food is wasted each year in the United Kingdom. In total, 20 million ton of food waste is produced annually in the United Kingdom, with the producers, processors, institutions, retailers, and others involved outside the household accounting for 13 million ton. Taking food stuffs specifically 4.4 million apples, 1 million slices of ham, and 440,000 ready meals per day are thrown away. The report claims that this involved 18 million ton of CO_2 emissions, because every tonne of food waste means 4.5 ton of CO_2 emissions. In the developing world, people spend up to 80% of their income on food: the price of food has risen by over 50% in 2008, on top of a 27% rise in 2007, according to the UN's Friends of the Earth (FOE). FOE also admits that just 0.36% of the UK's electricity needs could be met by anaerobic digestion (AD), if 5.5 million ton of food waste was treated by AD, it could only generate enough electricity to power 164,000 houses.

In the western world, food is produced, processed, transported, sold, driven home and then, 33% of the time, thrown into the bin for landfill. Then in landfill, methane gas is given off, which is far more destructive than CO_2. Fresh fruits, vegetables, and salads make up the largest category of waste, according to the The UK's Waste & Resources Action Program (WRAP) report, clocking in at 1.4 million ton per year (Moore, 2008).

Furthermore, every year the European food-processing industry produces vast volumes of aqueous wastes. These include: fruit and vegetable residues and discarded items, molasses, and bagasse from sugar refining, bones, flesh, and blood from meat and fish processing, stillage and other residues from wineries, distilleries and breweries, dairy wastes such as cheese whey, and wastewaters from washing, blanching and cooling operations (Arora *et al.,* 2002). Many of these contain low levels of suspended solids and low concentrations of dissolved materials. Apart from the environmental challenges posed, such streams represent considerable amounts of potentially reusable materials and energy. Much of the material generated as wastes by the food-processing industries throughout Europe—and about to be generated within bio-fuels programs—contains components that could be utilized as substrates and nutrients in a variety of microbial/enzymic processes, to give rise to added-value products. Varieties of processes exist that do this worldwide, some having operated for many years. Joshi (2002) and Marwaha and Arora's studies (2000) are two examples of extensive discussions of current industrial exploitation and future possibilities within this area. Added-value products actually produced from food industry wastes, or potentially so, include animal feed, single-cell protein (SCP) and other fermented edible products, baker's yeast, organic acids, amino acids, enzymes (e.g., lipases, amylases, cellulases), flavors and pigments, the bio-preservative bacteriocin (from the culture of *Lactococcus lactis* on cheese whey) and microbial gums and polysaccharides (Joshi, 2002).

According to the European Landfill Directive, the amount of biodegradable waste sent to landfills in member countries by 2020 must reach 35% of the levels reached in 1995. Therefore, the European food-processing industry operations are having to comply with increasingly more stringent EU environmental regulations related to disposal or utilization of by-products and wastes. These include growing restrictions on land spraying with agro-industrial wastes, and on disposal within landfill operations, and the requirements to produce end products that are stabilized and hygienic. Unless suitable technologies are found for the processing and utilization of waste by-products, large numbers of food-processing operations will be under threat.

The aim of this work is to provide a comprehensive literature survey on food waste processing technologies, published during the last 15 years. This chapter consists of three parts: the first describes the upgrading concept, for example, recovery of added-value products; the second summarizes the latest knowledge in the field of treatment technologies and our own investigations; the third part is related to the food chain management (FCM) for sustainable food system development. The aim of the final part is to summarize recent research on user-oriented innovation in the food sector, emphasizing on circular structure of a sustainable economy. When discussing the environmental impact of food production it is important to use a holistic approach, which can integrate the environmental aspects into the product development and food production. As the food supply chain is complex, environmental impacts can occur in different places and different times for a single food product. Life cycle assessment (LCA) provides a way of addressing this problem. LCA gives businesses the opportunity to anticipate environmental issues and integrate the environmental dimension into products and processes. Important issues directly related to food processing are energy and waste management. Food production in general uses significant amounts of energy and produces relatively large amounts of wastes, particularly, packaging wastes.

B. Development of green production processes

The waste management hierarchy is one of the guiding principles of the zero waste practice (Fig. 3.1). By analogy with this principle, the development of green production processes can be achieved following the short-, medium-, and long-term goals (Laufenberg *et al.*, 2003).

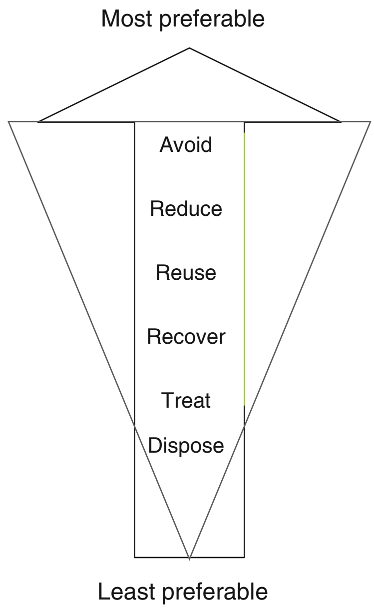

FIGURE 3.1 The food waste management hierarchy.

1. *Short-term goals* involve waste minimization by reduction and recycling of valuable substances, by-products and residues with reduction of emission and risk as a final outcome.
2. *Medium-term goals* include development of efficient production process, adding value to by-products. The outcome for the companies is their higher environmental responsibility accompanied by competitive advantages.
3. *Long-term goals* consist of step-by-step implementation of environmentally friendly manufacturing, developing "innovative products." The ultimate outcome is design of innovative food products like functional foods, which can open new markets and meet green productivity objectives.

1. Holistic approach in food production

When discussing the environmental impact of food production it is important to use a holistic approach. This approach tries to connect different goals, such as highest product quality and safety, highest production efficiency and the integration of environmental aspects into product development and food production. Within the concept every factor and aspect should be taken into account in a coherent manner (Laufenberg *et al.*, 2003). Present R&D in food technology is unthinkable without taking environmental aspects into account. A responsible management of inadequate resources is needed especially in view of tighter living spaces. Based on these considerations, the holistic concept of food production shown in Fig. 3.2 has been developed.

2. Green production strategy

Green or clean production can be considered so far as a strategic element in manufacturing technology for present and future products in several industrial branches. Demand is focused on the development of cost-effective technology, the optimization of processes including separation steps, alternative processes for the reduction of wastes, optimization of the use of resources and improvement in production efficiency (Paul and Ohlrogge, 1998). Hence current industrial waste management techniques can be classified into three options: source reduction *via* in-plant modification, waste recovery/recycle or waste treatment by detoxifying, neutralizing or destroying the undesirable compounds. The first two options plant modification and waste recovery/recycle represent the most promising waste management strategies. Indeed, waste recovery is a particularly attractive option. Significant environmental and economic benefits can accrue from separating industrial wastes with the objective of recycling/reusing these valuable components and/or the bulk of water.

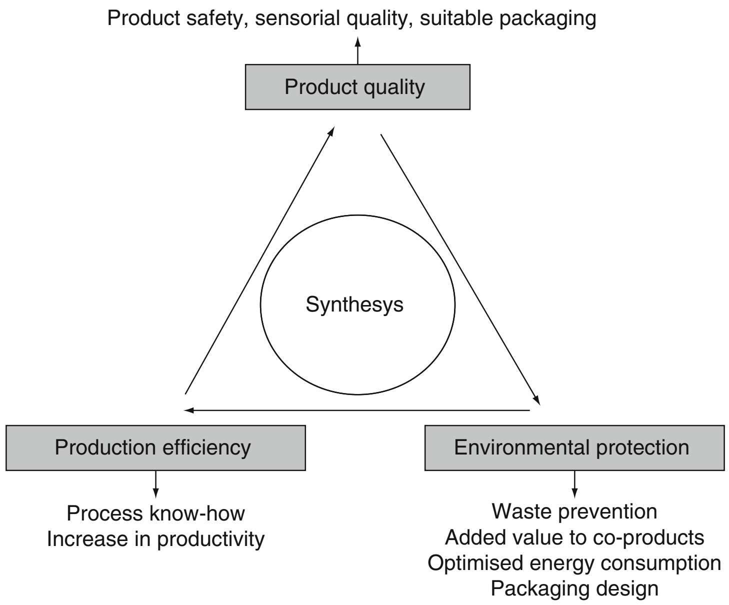

FIGURE 3.2 The holistic concept of food production (Laufenberg *et al*., 2003).

Promising concepts include pervaporation in hybrid processes (Hausmanns *et al*., 1999) or the upgrading of vegetable residues to create a secondary use for the ''waste products'' (Laufenberg *et al*., 1999). The goal of green production is to fulfill our need for products in a *sustainable way*, that is, using renewable, nonhazardous materials and energy efficiently while conserving bio-diversity. Clean production systems are *circular* and use fewer materials and less water and energy, as a result resources flow through the production–consumption cycle at slower rates (Fig. 3.3).

II. SOURCES AND CHARACTERIZATION OF FOOD WASTES

A. Fruit-and-vegetable wastes

Fruit-and-vegetable wastes (FVWs) are produced in large quantities in markets and constitute a source of nuisance in municipal landfills because of their high biodegradability (Misi and Forster, 2002). For example, in the central distribution market for food (meat, fish, fruit, and vegetables) Mercabarna (Barcelona), the total amount of wastes coming from fruit and vegetables is around 90 ton per day during 250 days per year (Mata-Alvarez *et al*., 1992). The whole production of FVW collected from the market of Tunisia has been measured and estimated to be 180 ton per month (Bouallagui *et al*., 2003). In India, FVW constitute about 5.6 million ton annually and currently these wastes are disposed by dumping on the outskirts of cities (Srilatha *et al*., 1995). The wastes from fruit-and-vegetable processing industries generally contain large amounts of suspended solids (SS) and high values of biological (BOD)

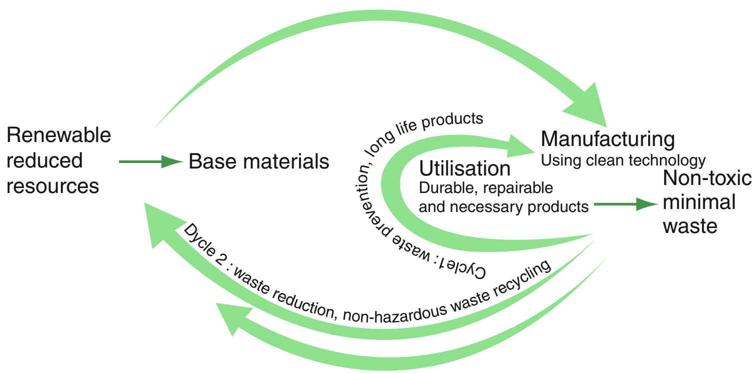

FIGURE 3.3 Circular structure of a sustainable economy (Stahel, 2008).

and chemical oxygen demands (COD). Other parameters of interest are pH, dissolved oxygen tension, concentration of total solids (TSs). Indicative values of BOD, COD, SS, and pH for the processing of some fruit and vegetables are summarized in Table 3.1.

According to Verrier *et al*. (1987) and Ruynal *et al*. (1998), the total initial solid concentration of FVW is between 8 and 18%, with a total volatile solids (VSs) content of about 87%. The organic fraction includes about 75% sugars and hemicellulose, 9% cellulose and 5% lignin. In general, these wastes consist of hydrocarbons and relatively small amounts of proteins and fat with an acidic pH (Riggle, 1989), and moisture content of 80–90% (Grobe, 1994). The wastewaters contain dissolved compounds, pesticides, herbicides, and cleaning chemicals.

B. Olive oil industry

Liquid waste from olive oil industry is a dark-colored juice, which contains organic substances such as sugars, organic acids, poly-alcohols, pectins, colloids, tannins, and lipids (Table 3.2). The difficulty of disposing olive oil mill wastewaters (OMW) is mainly related to its high BOD, COD, and high concentration of organic substances; for example, phenols, which make degradation a difficult and expensive task (Saez *et al*., 1992).

C. Fermentation industry

The fermentation industry is divided into three main categories: brewing, distilling, and wine manufacture. Each of these industries produces liquid waste with many common characteristics, such as high BODs and CODs, but differs in the concentration of the organic compounds such as tannins,

TABLE 3.1 Fruit-and-vegetable waste characteristics (Thassitou and Arvanitoyannis, 2001)

Waste characteristics				
Fruit/vegetable	BOD (mg/L)	COD (mg/L)	SS (mg/L)	pH
Apples	9600	18700	450	5.9
Carrots	1350	2300	4120	8.7
Cherries	2550	2500	400	6.5
Corn	1550	2500	210	6.9
Grapefruit	1000	1900	250	7.4
Green peas	800	1650	260	6.9
Tomatoes	1025	1500	950	7.9

TABLE 3.2 Chemical composition of organic fraction and quality characteristics of liquid olive oil waste (Thassitou and Arvanitoyannis, 2001)

Components	Values (%)	Parameters	Values
Lipids	1.0–1.5	pH	3–5
Organic acid	0.5–1.55	SS	65,000 mg/L
Pectins, colloids, tannins	1.0–1.5	TS	6.39%
Sugars	2.0–8.0	BOD	43,000 mg/L
Total nitrogen content	1.2–1.5	COD	100,000 mg/L

phenols, and organic acid. The difficulty in dealing with fermentation wastewaters is in the flows and loads of the waste.

D. Dairy industry

The dairy industry represents a major and important part of the food industry and contributes significant liquid wastes, whose disposal requires a large amount of capital investment. On the basis of cheese consumption and production details (British Cheese Board, 2004), it is estimated that approximately 9 million ton of cheese *per annum* is produced within the EU, giving rise to an annual whey production figure of the order of 50 million m^3. About 50% of total world cheese-whey production is treated and transformed into various food products, of which about 45% is used directly in liquid form, 30% in the form of powered cheese whey, 15% as lactose and de-lactosed by-products, and rest as cheese-whey-protein concentrates. Waste from the dairy industries contributes substantially to the pollution of surface waters and soil. Some of their characteristics can be summarized as follows: high organic load (e.g., fatty acids and lactose), considerable variations in pH (4.2–9.4), relatively large load of suspended solids (0.4–2 g/L), and large variations in waste supply. The dairy wastewater may contain proteins, salts, fatty substances, lactose, and various kinds of cleaning chemicals (Kosseva *et al.*, 2003). The presence of detergents and their additives in dairy wastewater hardly influences the total COD in contrast to milk, cream or whey, the high CODs of which are likely to have a dominating effect (Table 3.3). Detergents may be alkaline or acid, and very often contain additives like phosphates, sequestering agents, surfactants, and so on. EDTA is commonly used as a substitute for polyphosphates. It has a low biodegradability and remains in the wastewater after treatment. Surfactants have been shown to affect strongly the ecosystems of rivers and are toxic to aquatic animals (Thassitou and Arvanitoyannis, 2001).

TABLE 3.3 Characteristics of dairy waste effluents (combined from Wildbrett, 1988; Demirel *et al*., 2005)

Product/substance	Concentration (g/L)	COD (g/L)	BOD (g/L)	pH	Suspended solids (g/L)	Volatile solids (g/L)
Cream, 30% fat	–	850–860	1.20–4.00	8–11	0.35–1.00	0.33–0.94
Whole milk, 3.5% fat	–	760–210		6.92	0.34–1.73	0.255–0.83
Skim milk	–	9–100	0.50–1.30	6.92	0.09–0.45	
Whey	–	68–75		3.5–6.5	0.50–2.50	
Na-dodecyl benzol sulfonate	0.1	0.216				
Na-ethoxy alkyl sulphate	0.1	0.178				
Dialkyl dimethyl ammonium chloride (C_{18}–C_{20})	0.1	0.235				
Sodium hydroxide	10.0	0				
Phosphoric acid	10.0	0				
Detergent and disinfectant 1 (with QAC)	10.0	2250				
Detergent and disinfectant 2	10.0	0.017				
Detergent and disinfectant 3 (with surfactant)	5.0	0.147				

E. Meat and poultry industry

Meat, poultry, and fish industries produce the highest loads of waste within the food industry. The meat industry contains slaughterhouses and processing units where meat is prepared, cut in pieces and is either frozen, cooked, cured, smoked, or made into sausages. Slaughterhouses are more important than the other units in terms of environmental pollution. The wastes coming from these units contain various quantities of blood, fats, residues from the intestine, paunch grass, and manure (Cournoyer, 1996). Slaughterhouse wastewater is typically high in both moisture (90–95%) and nitrogen, has a high BOD, and is odorous. Proper management is a prerequisite to ensure that potentially high levels of pathogens are eliminated. Cooper and Russell (1992) investigated and published a summary of the treatment technologies of 44 meat processing plants in New Zealand. The management of nitrogen in both land application and direct discharge to receiving water was the critical point. The operation of a pilot-scale UASB treating the effluent from a beef slaughtering operation was reported by Torkian *et al.* (2003a). The researchers were able to obtain steady-state operation of the UASB at organic loading rates (OLRs) of 13–39 kg soluble COD/m^3 day and HRTs of 2–7 h under mesophilic conditions. SCOD removals of 75–90% were obtained at these loading rates with influent feed concentrations of 3000–4500 mg soluble COD/L. In a connected study, the effluent from the UASB was processed through a pilot-scale rotating biological contactor (RBC) to obtain additional organic load reduction (Torkian *et al.*, 2003b). At OLRs of 5.3 g soluble BOD/m^3 day, soluble BOD removals of 85% were obtained, with a vast majority occurring within the first half of the six-stage reactor. As part of a wastewater treatability study, Del Pozo *et al.* (2003) noted that the high COD concentrations (7230 mg/L) warranted anaerobic treatment and conducted a series of anaerobic batch tests on a beef slaughterhouse wastewater that yielded COD removals of 80%.

Bohdziewicz *et al.* (2003) were successful in obtaining high contaminant removals from a meat processing wastewater using ultrafiltration followed by reverse osmosis. Total Phosporous and Total Nitrogen were removed at greater than 98% efficiencies, and BOD and COD removals were greater than 99%. Membrane fouling has commonly been cited as the primary impediment to the use of filtration technologies in the meat processing industry. Allie *et al.* (2003) reported on the use of lipases and proteases to effectively remove fouling proteins and lipids from flat-sheet polysulphone ultrafiltration membranes.

Poultry wastes are equally problematic to meat wastes. Starkey (2000) reviewed the considerations for selection of a treatment system for poultry processing wastewater, including land availability, previous site history, publicly owned treatment work discharge, conventional waste treatment systems, and land application systems. The performance of anaerobic treatment systems, including lagoons, contact processes, sludge beds, filters, packed beds, and hybrid reactors were outlined (Ross and Valentine, 1992). In another study on combined treatment, anaerobic and aerobic fixed-film reactors in tandem were used for the treatment of poultry processing wastewater (Del Pozo and Diez, 2003). COD removals of 92% were observed with system OLRs of 0.39 kg COD/m^3 day and 95% total Kjeldahl nitrogen (TKN) removals for applied N loads of 0.064 kg TKN/m^3 day. The authors reported the effects on nutrient and organic removals at varying recycle rates between the two reactors and varying reactor size. Pretreatment is also regarded as necessary for poultry waste to reduce the moisture and increase the porosity with the addition of bulking agents, which also increase the aeration and carbon level in wastewater. Proper treatment is needed to eliminate the pathogens.

F. Seafood by-products

One of the most important environmental problems which are characteristic of coastline areas is the large volume of waste generated by fishing, aquaculture, or foodstuff processing industries. Usually, these by-products are dumped into the sea without a previous treatment of depuration neither evidently nor by valorization. Among these food products, the cooked cephalopod (particularly octopus) has higher commercial value and larger production of wastewater, particularly in the NW Spain (Vazquez and Murado, 2008). These massive spills with high protein concentration generate a negative environmental impact on the marine ecosystems. Over the past two decades, the shellfish industry has also experienced a significant expansion, making crustacean wastes materials available concentrated in some areas and in larger quantities. The most commercially harvested crustacean species are crab, shrimp, prawn, Antarctic krill, and cray fish. In the year 2005–2006, 145,180 Gg of frozen shrimps were produced, and it can be estimated that nearly 150,000–175,000 Gg of shrimp waste per annum to be generated from shrimp processing companies in India (Babu *et al.*, 2008). Use of these crustaceous wastes has been of interest to researchers for two reasons: (1) these wastes are highly perishable and create environmental pollution (Tan and Lee, 2002). (2) They are the rich sources of protein, chitin, and carotenoids. These large quantities of waste materials are useful in production of chitin, which is the second most abundant natural polymer on Earth (Table 3.4).

Tuna including yellowfin, skipjack, bluefin, albacore, and bigeye is one of the worldwide favorite fish species (Aewsiri *et al.*, 2008). The total catch of tuna in the world has increased continuously from 0.4 to 3.9

TABLE 3.4 Proximate composition of shrimp shell and crab (Santhosh and Mathew, 2008)

Parameter	Shrimp shell (%)	Crab (%)
Moisture	75–80	70
Ash (dry basis)	30–35	45–50
Protein (dry basis)	35–40	30–35
Chitin (dry basis)	15–20	13–15
Fat (dry basis)	3–5	1.0–1.5

million metric ton from 1950 to 2000 (Miyake *et al*., 2004). In Thailand, tuna is usually processed as canned products, which are exported to many countries over the world. During the processing, a large amount of wastes involving skin, bone, and fin is generated (Shahidi, 1994). These wastes are commonly utilized as low value fish meal or fertilizer. So far, the utilization of fish processing wastes has been paid increasing attention as the promising means to increase revenue for producer and to decrease the cost for disposal or management of those wastes. Fishery wastes can be used for enzyme recovery (Klomklao *et al*., 2005), protein hydrolyzate production (Slizyte *et al*., 2005), collagen extraction (Fernandez-Dıaz *et al*., 2001; Muyonga *et al*., 2004a), and gelatin extraction (Choi and Regenstein, 2000; Muyonga *et al*., 2004b).

III. RECOVERING OF ADDED-VALUE PRODUCTS FROM FVW (UPGRADING CONCEPT)

A. Challenge for the vegetable industry

Considering the vegetable industry, the green production goals could be fulfilled by the usual approaches such as minimization, disposal, feeding, fertilization/composting, closed loop production, or conversion (Laufenberg, 2003). The upgrading concept tries to add value to the by-products and residues. This medium-term goal results in the creation of innovative and industrially important metabolites and products like:

- Flavors produced by bioconversion of waste material or solid-state fermentation (SSF)
- Dietary fibers as matrices for flavors, dyes, or antioxidants
- Pectin and gelling agents with defined properties using synergetic effects
- Designer dietary fibers for application in bread or beverages

- Effective and low-cost bioadsorbents, which can be easily desorbed or biodegraded after use
- Hybrid processes combining adsorption and membrane processes for an advanced wastewater treatment and internal process water recycle

Thus the introduced concept is a further step toward environmentally gentle manufacturing. The concept does not present any immediate patent solutions or recipes, because industrial food production is an interactive process, which needs to fulfill all three conditions: quality, efficiency, and environmental protection as mentioned above. The result is a step-by-step waste reduction with simultaneously rising productivity, not obtained by restrictions but by opportunities.

The advantages for industry and environment are as follows:

- Closed loop of valuable constituents
- Preservation of resources
- Discovery of niche markets
- Environmental protection, combined with
- Reduced waste disposal costs

Important factor for the upgrading process is the development of a procedure using technical standard equipment. Goal of the upgrading is a product with desired, reproducible properties designed under economical and ecological conditions.

B. SSF of fruit/vegetable by-products

The exploitation of by-products of fruit and vegetable processing as a source of functional compounds and their application in food is a promising field. The highly valuable composition of apple pomace and possible strategies of utilization by SSF have recently been reviewed by Vendruscolo *et al.* (2008).

1. Apple pomace

Apple pomace and its aqueous extract present a great potential for use as substrates in biotechnological processes. It is a heterogeneous mixture consisting of peel, core, seed, calyx, stem, and soft tissue (Grigelmo-Miguel and Martın-Belloso, 1999). It has high water content and is mainly composed of insoluble carbohydrates such as cellulose, hemicellulose, and lignin. Simple sugars, such as glucose, fructose, and sucrose, as well as small amounts of minerals, proteins, and vitamins, are part of apple pomace composition (Jin *et al.*, 2002; Zheng and Shetty, 2000a). The pomace is very inexpensive and is abundantly available during the harvesting season, and several microorganisms can use this apple residue as a substrate. Bacteria, yeast, and fungi have been cultivated on apple pomace for different purposes. Filamentous fungi, especially basidiomycetes, are the most suitable microorganisms for growing on fruit processing residues. Table 3.5 presents a list of different biotechnological applications of apple pomace, with the respective microorganism and the fermentation process applied (Vendruscolo *et al.*, 2008) with the following abbreviations: SSF—solid-state fermentation; SmF—submerged fermentation.

Several studies and patents have been described regarding the employment of this residue for the production of value-added compounds, such as enzymes, SCP, biopolymers, fatty acids, polysaccharides, and organic acids, among others. Biotechnological applications of the apple pomace are interesting not only from the point of view of low-cost substrate, but also in solving problems related to the disposal of the pomace, a pollution source that has been gaining a lot of attention in apple-producing areas. Several operational variables must be considered and optimized to effectively use the apple pomace in bioprocesses; strain type, reactor design, aeration, pH, moisture, and nutrient supplementation are only a few examples of these fundamental process variables that are crucial for the economic viability of using the apple pomace as a substrate for biotechnological applications.

2. Production of enzymes

The most important area of apple pomace utilization is the production of enzymes. Polygalacturonases or hydrolytic depolymerases are enzymes involved in the degradation of pectic substances. They have a wide range of applications in food and textile processing, degumming of plant rough fibers, and treatment of pectic wastewaters. Seyis and Aksoz (2005) investigated the use of apple pomace, orange pomace, orange peel, lemon pomace, lemon peel, pear peel, banana peel, melon peel, and hazelnut shell as substrate for xylanase production using *Trichoderma harzianum*. The maximum enzyme activity was observed when melon peel was used as the substrate for SSF, followed by the apple pomace and hazelnut shell.

Villas-Boas *et al.* (2002) found a novel lignocellulolytic activity of *Candida utilis* during SSF on apple pomace. Hydrolytic and oxidative enzymes of *C. utilis*, excreted to the culture medium during solid-substrate cultivation, were identified, evaluated, and quantified. The soluble lignin fraction of the apple pomace was consumed at very significant levels (76%), when compared to the nonfermented apple pomace. The enzyme produced by *C. utilis* with the highest activity was a pectinase (23 U/mL). The yeast showed a significant manganese-dependent peroxidase activity (19.1 U/mL) and low cellulase (3.0 U/mL) and xylanase (1.2 U/mL) activities, suggesting that *C. utilis* has the ability to use lignocellulose as a substrate.

TABLE 3.5 Bioprocesses using apple pomace as substrate (Vendruscolo *et al.*, 2008)

Application	Microorganism	Process	References
Enzyme production:			
β-glucosidase	*Aspergillus foetidus*	SSF	Hang and Woodams (1994)
Lignocellulolytic enzymes	*Candida utilis*	SSF	Villas-Boas *et al.* (2002)
Pectin methylesterase	*Aspergillus niger*	SSF/SmF	Joshi *et al.* (2006)
Pectinases	*Polyporus squamosus*	SmF	Pericin *et al.* (1999)
Pectolytic enzymes	*A. niger*	SSF	Berovic and Ostroversnik (1997)
Polygalacturonase	*Lentinus edodes*	SSF	Zheng and Shetty (2000b)
Aroma compound production:			
Aroma compounds	*Rhizopus sp. Rhizopus oryzae*	SSF	Christen *et al.* (2000)
Aroma compounds	*Kluyveromyces marxianus*	SSF	Medeiros *et al.* (2000)
Fruity aroma	*Ceratocystis fimbriata*	SSF	Bramorski *et al.* (1998)
Phenolic compounds	*Trichoderma viride Trichoderma harzianum Trichoderma pseudokoningii*	SSF	Zheng and Shetty (2000a)
Nutritional enrichment:			
Animal feed	*Gongronella butleri*	SSF	Vendruscolo (2005)
Nutritional enrichment	*Candida utilis Kloeckera sp.*	SSF	Devrajan *et al.* (2004)
Protein enrichment	*Rhizopus oligosporus*	SSF	Albuquerque *et al.* (2006)

(*continued*)

TABLE 3.5 (*continued*)

Application	Microorganism	Process	References
Heteropolysaccharide production:			
Chitosan	*G. butleri*	SSF	Streit *et al.* (2004)
Chitosan	*G. butleri*	SmF	Streit *et al.* (2004) and Vendruscolo (2005)
Heteropolysaccharide	*Beijerinckia indica*	SmF	Jin *et al.* (2002)
Xanthan	*Xanthomonas campestris*	SSF	Stredansky and Conti (1999)
Other products:			
Citric acid	*A. niger*	SSF	Shojaosadati and Babaeipour (2002)
Ethanol	*S. cerevisiae*	SSF	Ngadi and Correa (1992a)
γ -*Linolenic acid*	*Thamnidium elegans* *Mortierella isabelina* *Cunninghamella elegans*	SSF	Stredansky *et al.* (2000)

Recently, Joshi *et al.* (2006) reported the production of pectin methylesterase by *Aspergillus niger* using apple pomace as culture medium comparing the SmF and SSF. The pectin methylesterase activity was 2.3 times higher when produced by SSF than by SmF. This study corroborates the fact that SSF is the more adequate process for apple pomace bioconversion.

Dry citrus peels are rich in pectin, cellulose, and hemicellulose and may be used as a fermentation substrate. Production of multienzyme preparations containing pectinolytic, cellulolytic, and xylanolytic enzymes by the mesophilic fungi *A. niger* BTL, *Fusarium oxysporum* F3, *Neurospora crassa* DSM 1129, and *Penicillium decumbens* under SSF on dry orange peels was enhanced by optimization of initial pH of the culture medium and initial moisture level (Mamma *et al.*, 2008). Under optimal conditions *A. niger*

BTL was by far the most potent strain in polygalacturonase and pectate lyase, production followed by *F. oxysporum* F3, *N. crassa* DSM 1129, and *P. decumbens. N. crassa* DSM 1129 produced the highest endoglucanase activity and *P. decumbens* the lowest one. Comparison of xylanase production revealed that *A. niger* BTL produced the highest activity followed by *N. crassa* DSM 1129, *P. decumbens* and *F. oxysporum* F3. *N. crassa* DSM 1129 and *P. decumbens* did not produce any b-xylosidase activity, while *A. niger* BTL produced approximately 10 times more b-xylosidase than *F. oxysporum* F3. The highest invertase activity was produced by *A. niger* BTL while the lowest ones by *F. oxysporum* F3 and *P. decumbens*. After SSF of the four fungi, under optimal conditions, the fermented substrate was either directly exposed to autohydrolysis or new material was added, and the *in situ* produced multienzyme systems were successfully used for the partial degradation of orange peels polysaccharides and the liberation of fermentable sugars.

Feruloyl esterase (FAE) and xylanase activities were detected in culture supernatants from *Humicola grisea* var. *thermoidea* and *Talaromyces stipitatus* grown on brewers' spent grain (BSG) and wheat bran (WB), two agro-industrial by-products. Maximum activities were detected from cultures of H. grisea grown at 150 rpm, with 16.9 and 9.1 U/ml of xylanase activity on BSG and WB, respectively. Maximum FAE activity was 0.47 and 0.33 U/ml on BSG and WB, respectively. Analysis of residual cell wall material after microbial growth shows the preferential solubilization of arabinoxylan and cellulose, two main polysaccharides present in BSG and WB. The production of low-cost cell-wall-deconstructing enzymes on agro-industrial by-products could lead to the production of low-cost enzymes for use in the valorization of food-processing wastes (Mandalari *et al*., 2008).

3. Production of aroma compounds

The European Community guidelines 88/388/ EWG and 9/71/EWG subdivide flavors/aromas into six categories, the first of which describes regulations for the food labeling as ''natural flavor.'' Natural flavors are chemical substances with aroma properties that are produced from feedstock of plant or animal origin by means of physical, enzymatic, or microbiological processing. The microbial synthesis of these natural flavors is generally carried out by SmF. Due to the high costs of this currently used technology on an industrial scale, there is a need for developing low-cost processes even for cheaper molecules like benzaldehyde. This could be achieved by exploration of the metabolic pathways and by alternative technology such as SSF (Couto, 2008). The use of biotechnology for the production of natural aroma compounds by fermentation or bioconversion using microorganisms is an economic alternative to the difficult and expensive extraction from raw materials such as plants (Daigle *et al.*, 1999). Currently, it is estimated that around 100 different aroma compounds are produced commercially by fermentation (Medeiros *et al.*, 2006). Furthermore, the world market of aroma chemicals, fragrances, and flavors has a growth rate of 4–5% per year. Because of a higher consumer acceptance there is an increasing economic interest in natural flavors (Table 3.6).

Bramorski *et al.* (1998) analyzed the production of aroma compounds by *Ceratocystis fimbriata* under seven different medium compositions (prepared by mixing cassava bagasse, apple pomace, amaranth, and soya bean). The aroma production was growth dependent, and the maximum aroma intensity was detected in a few hours around the maximum respirometric activity. The medium containing apple pomace produced a strong fruity aroma after 21 h of cultivation. This same medium was used by Christen *et al.* (2000) for the production of volatile compounds by *Rhizopus* strains. Authors found that the production of volatile compounds was related mainly to the medium used, and no difference was observed among the strains studied. The odors detected have a slight alcoholic note, and the apple pomace produced intermediate results, compared with the amaranth grain supplied with mineral salt solution.

Another source of aroma compounds is grape pomace, the main by-product of wine production, which consists of skins, seeds, and stalks, reaching an estimated amount of 13% by weight of processed grape (Torres *et al.*, 2002). The chemical composition of grape pomace is rather complex: alcohols, acids, aldehydes, esters, pectins, polyphenols, mineral substances, sugars, and so on are the most represented classes of compounds (Mantell *et al.*, 2003; Murthy *et al.*, 2002). The evaluation of the qualitative aspects of a grape pomace is carried out in view of the production of high-quality grappa; otherwise the grape pomace is used for alcohol distillation, or thrown away. The best grape pomaces are highly rich in vinous liquid with a moisture degree ranging from 55% to 70%, which allows to exploit the raw material better and to extract the organoleptic characteristics of the native vine. The volatile components of a grape pomace were recent studied and reported by Ruberto *et al.* (2008). Percentages of compounds were determined from their peak areas in the GC–FID profiles, using gas chromatograph with a flame ionization detector and gas chromatography–mass spectrometry.

4. Production of ethanol

A solid-state fermentation process for the production of ethanol from apple pomace by *Saccharomyces cerevisiae* was described by Khosravi and Shojaosadati (2003). A moisture content of 75% (wt/wt), an initial sugar concentration of 26% (wt/wt), and a nitrogen content of 1% (wt/wt) were the conditions used to obtain 2.5% (wt/wt) ethanol without saccharification and 8% (wt/wt) with saccharification. The results indicate that

TABLE 3.6 Flavors and biofine chemicals produced by SSF of vegetable residues (selection from Laufenberg, 2003)

Year	Residual matter	Description/conversion principle	Product
2000	Spent malt grains, apple pomace (Stredansky *et al.*, 2000)	*T. elegans* CCF 1456 degraded the substrate in a ratio of 3 to 1 (AP to SMG), precursor peanut oil even increased the yield	γ-Linolenic acid was produced in a yield of 5.17 g per kg dry substrate; with peanut oil precursor 8.75 g/kg DM
2000	Cassava bagasse, apple pomace (Christen *et al.*, 2000)	Four strains of *Rhizopus*, two residues and two precursors, mixed substrate combinations	Volatile carbons as flavors; acetaldehyde, ethanol, propanol, esters
1997	Cassava bagasse, wheat bran and sugarcane bagasse (Bramorski *et al.*, 1998)	*C. fimbriata*, ability to generate fruity aromas in dependence on the substrate used	Banana flavor and fruity complex flavors
1994	Citrus, apple, sugar beet pomace (Grohmann and Bothast, 1994)	Microbial conversion by enzymatic hydrolysis	Pectin, substrate, liquid biofuel
1998	Cranberry pomace (fish offal) (Zheng and Shetty, 1998)	*Trichoderma viride*, *Rhizopus* $CaCO_3$ was added as neutralizer, water for aw adjustment	Polymeric dye decolorizing isolate for wastewater treatment, extracellular enzymes

2001	Linseed cake, castor oil cake, olive press cake, sunflower cake (Laufenberg *et al.*, 2001)	*Moniliella suaveolens*, *Trichoderma harzianum*, *Pityrosporum ovale*, and *Ceratocytis moniliformis* form decalactones (problems with phenolic components)	Acceptable yields on olive press cake and castor oil cake, d- and c-decalactone are produced
1998	Olive cake, sugarcane bagasse (Cordova *et al.*, 1998)	Lipase degrading fat in olive cake	Enzyme product applied in bakery goods, confectionery, pharmaceuticals
1999	Olive pomace (Haddadin *et al.*, 1999)	Four microorganisms, delignification, saccharification with *Trichoderma* sp., biomass formation with *Candida utilis* and *Saccharomyces cerevisiae*	Crude protein enriched from 5.9% to 40.3%. Source for animal fodder
1995	Pineapple waste (Tran and Mitchell, 1995)	*A. foetidus* produces citric acid 16.1 g/100 g DM and 3% methanol	Pharmaceuticals, food industry, preserving agent
1997	Potato waste (Lucas *et al.*, 1997)	Amylases	Bakery goods, breweries, textile industry
1997	Sugar beet pulp, cereal bran (Asther *et al.*, 1997)	Commensalism of two microorganisms degrading the substrate	Flavor vanillin
1994	Tomato pomace (Carvalheiro *et al.*, 1994)	Co-cultures of *Trichoderma reesei* and *Sporotrichum* sp. are degrading cellulose and hemicellulose fraction	67% less cellulose, 73% less hemicellulose, enhanced lignin and protein content

the alcohol fermentation from apple pomace is an efficient method to reduce waste disposal, with the concomitant production of ethanol.

Nogueira *et al.* (2005) evaluated the alcoholic fermentation of the aqueous extract of apple pomace. Apple juice, pomace extract, and pomace extract added with sucrose provided after fermentation 6.90%, 4.30%, and 7.30% ethanol, respectively. A fermentation yield of 60% was obtained when pomace extract was used, showing that it is a suitable substrate for alcohol production.

For bioconversion of bean curd refuse, a processing by-product of bean curd, ethanol-producing anaerobic thermophiles were newly isolated. Both of them degraded hemicellulose, but not cellulose at all. Phylogenetically, strains belong to the *Clostridium* and *Thermoanaerobacterium* genus. Aerobic thermophiles degrading cellulose were also newly isolated. This strain belongs to the *Geobacillus* genus phylogenetically. The co-culture also significantly reduced CH_3SH production, leading to the prevention of offensive odor (Miyazaki *et al.*, 2008).

5. Production of organic acids

Shojaosadati and Babaeipour (2002) used apple pomace as substrate for the production of citric acid using *A. niger via* SSF in column reactors. They evaluated several cultivation parameters, such as aeration rate (0.8, 1.4, and 2.0 L/min), bed height (4, 7, and 10 cm), particle size (0.6–1.18, 1.18–1.70, and 1.70–2.36 mm), and moisture content (70%, 74%, and 78%). For citric acid yield, the aeration rate and particle size were the most important parameters. Neither the bed height nor the moisture content was found to significantly affect citric acid production. The operating conditions that maximized citric acid production consisted of low aeration rate (0.8 L/min), high bed height (10 cm), large particle size (1.70–2.36 mm), and elevated moisture content (78%).

Apple pomace has also been used for fatty acid production. Stredansky *et al.* (2000) evaluated the γ-linolenic acid (GLA) production in *Thamnidium elegans* by SSF. Apple pomace and spent malt grain were used as the major substrate components for the production of high-value fungal oil containing up to 11.43% biologically active GLA.

Apple pomace is a potential substrate for lactic acid production. Lactic acid has a number of applications in food technology (as acidulant, flavor, and preservative), pharmaceuticals and chemicals (Hofvendalh and Hahn-Hagerdal, 2000). The world market for lactic acid is growing every year, and its current production is about 150 million lb per year. The worldwide market growth is expected to be between 10% and 15% per year (Wassewar, 2005). When samples of apple pomace were subjected to enzymatic hydrolysis, the glucose and fructose present in the raw material as free monosaccharides were extracted at the beginning of the process. Using low cellulase and cellobiase charges (8.5 FPU/g-solid and 8.5 IU/ g-solid, respectively), 79% of total glucan was saccharified after 12 h, leading to solutions containing up to 43.8 g monosaccharides/L (glucose, 22.8 g/L; fructose, 14.8 g/L; xylose + mannose + galactose, 2.5 g/L; arabinose + rhamnose, 2.8 g/L). These results correspond to a monosaccharide/cellulase ratio of 0.06 g/FPU and to a volumetric productivity of 3.65 g of monosaccharides/L h. Liquors obtained under these conditions were used for fermentative lactic acid production with *Lactobacillus rhamnosus* CECT-288, leading to media containing up to 32.5 g/L of L-lactic acid after 6 h (volumetric productivity = 5.41 g/L h, product yield = 0.88 g/g) (Gullon *et al.*, 2008). Apple pomace shows several advantages as a raw material for lactic acid manufacture, including: (i) high content of free glucose and fructose, which are excellent carbon sources for lactic acid production (Hofvendalh and Hahn-Hagerdal, 2000); (ii) high content of polysaccharides (cellulose, starch, and hemicelluloses) which can be enzymatically hydrolyzed to give monosaccharides; (iii) presence of other compounds (e.g., monosaccharides other than glucose and fructose, di- and oligo-saccharides, citric acid, and malic acid) which can be metabolized by lactic bacteria (Carr *et al.*, 2002); and (iv) presence of metal ions (Mg, Mn, Fe, etc.) which could limit the cost of nutrient supplementation for fermentation media.

6. Production of polysaccharides

Jin *et al.* (2002, 2006) examined the potential of three agro-industrial by-products to be used as substrate for the production of heteropolysaccharide-7 (PS-7) by *Beijerinckia indica* in SmF under the same cultivation conditions. By-products from apple juice production, for example, soy sauce production, and the manufacturing processes of Sikhye (fermented rice punch), for example, a traditional Korean food, were tested. The apple pomace was found to be the best carbon source for PS-7 production compared to the other by-products, giving a production of 4.09 g/L after 48 h of cultivation. When Sikhye by-product was used as substrate, 3.00 g/L of PS-7 was formed, and using the soy sauce residue, 0.96 g/L of PS-7 was observed.

Xanthan gum is the most important microbial polysaccharide from the commercial point of view, with a worldwide production of about 30,000 ton/a. It has widespread commercial applications as a viscosity enhancer and stabilizer in the food, pharmaceutical and petrochemical industries (Papagianni *et al.*, 2001). The rheological behavior of the fermentation broth causes serious problems of mixing, heat transfer, and oxygen supply, thus limiting the maximum gum concentration achievable as well as the product quality (Wecker and Onken, 1991). Several strategies have been developed to overcome these problems including use of two-level impellers. The use of cheap substrates, instead of the commonly used glucose or sucrose, might result in a lower cost of the final product.

Stredansky and Conti (1999) proposed the use of SSF as an alternative strategy for the production of xanthan by *Xanthomonas campestris*, since solid substrates reproduce the natural habitat of this phytopathogenic bacterium. This technique allows overcoming problems connected with broth viscosity and, in addition, utilizes cheap substrates.

Streit *et al.* (2004) studied the production of fungal chitosan in SmF and SSF (column reactors) using the watery extract of apple pomace and the pressed apple pomace as substrate, respectively. Among the microorganisms studied, the fungus *Gongronella butleri* yielded the best results for the production of chitosan in SmF and SSF. Grown on the watery extract of apple pomace, the *G. butleri* presented the highest productivity (0.091 g/L h) and chitosan content in the biomass (0.1783 g/g of apple pomace) for a medium supplemented with 40 g/L of reducing sugars and 2.5 g/L of sodium nitrate.

Vendruscolo (2005) used an external loop airlift bioreactor for chitosan production by *G. butleri* CCT 4274 on the watery extract of apple pomace. The experiments using higher levels of aeration (0.6 volume of air per volume of liquid per minute) provided greater concentrations of biomass, attaining 8.06 and 9.61 g/L, in the production of 873 and 1062 mg/L of chitosan, respectively. These findings demonstrated the adequacy of the airlift bioreactor for the cultivation of microorganisms with emphasis on the production of chitosan.

7. Production of baker's yeast

Bhushan and Joshi (2006) used apple pomace extract as a carbon source in an aerobic-fed batch culture for the production of baker's yeast. The fermentable sugar concentration in the bioreactor was regulated at 1–2%, and a biomass yield of 0.48 g/g of sugar was obtained. Interestingly, the dough-raising capacity of the baker's yeast grown on the apple pomace extract was apparently the same as that of commercial yeast. The use of apple pomace extract as substrate is a useful alternative to molasses, traditionally used as a carbon source for baker's yeast production.

8. Production of pigments

Attri and Joshi (2005) used an apple pomace-based medium to examine the effect of carbon and nitrogen sources on carotenoid production by *Micrococcus* sp. Using 20 g/L of apple pomace in the basic medium provided the best growth conditions for the microorganism. Maximum biomass (4.13 g/L) and pigment (9.97 mg per 100 g of medium) yields were achieved when the medium was supplemented with 0.2% fructose. Optimal conditions for carotenoid production were 35 °C, pH 6.0, and cultivation time of 96 h. The same authors (Attri and Joshi, 2006) studied carotenoid production by *Chromobacter* sp. Using the same basic medium (20 g/L of apple pomace), they found a high production of biomass

(6.6 g/L) and carotenoids (46.6 mg per 100 g of medium) and with a shorter incubation period (48 h). These differences showed that the production of carotenoids can be improved by an accurate choice of organism.

Skin, rich in lycopene, is an important component of waste originating from tomato paste manufacturing plants (Kaur, *et al*., 2008). Lycopene is the principal carotenoid, causing the characteristic red hue of tomatoes (Shi and Le Maguer, 2000). Several epidemiological studies reported that lycopene-rich diets have beneficial effects on human health (Arab and Steck, 2000; Sharoni *et al*., 2000). A possible role has been suggested for tomatoes and tomato products in preventing cardiovascular disease and protecting against some types of cancer (based on lycopene content) (Willcox *et al*., 2003). Maximum lycopene (1.98 mg/100 g) was extracted when the solvent/meal ratio adjusted to 30:1 v/w, number of extractions—4, temperature 50 °C, particle size—0.15 mm, and extraction time—8 min (Kaur *et al*., 2008).

9. Feed protein

Song *et al*. (2005a) developed a method for producing SCP from apple pomace by dual SSF. This method comprises four different steps: (1) preparation of an SSF medium with pulverized apple pomace, (2) inoculating cultured mixed mature strain for SSF, (3) rapidly drying the resulting fermentation product at low temperature, and (4) subjecting the dried product to solid fermentation in another SSF medium to obtain the final product (patent no. CN 1673343). The same group of researchers (Song *et al*., 2005b) developed another method for producing feed protein by liquid–solid fermentation of apple pomace (patent no. CN 1663421). As compared with solid fermentation, this method has the advantage of reduced consumption of medium for seed culture, reduced cost, and applicability to large-scale production. The nutritional quality of a fibrous by-product or residue from a food manufacturing process was improved by inoculating it with filamentous fungus, and fermenting the fibrous product or residues was proposed by Power and Power (2005).

10. Antibiotics

Antibiotics are required in large quantity for the persistent fight against bacterial diseases; and so research has concentrated on producing them at the highest concentration with minimal energy input. Yang (1996) reported the production of oxytetracycline by *Strepfomyces rimosus* in SSF using corncob, a cellulosic waste, as a substrate. This author found that the oxytetracycline produced by SSF was more stable than that produced by SmF and the energy input was also less (Yang and Ling, 1989). In addition, the product presented the advantage that it could be temporarily stored without losing activity significantly. Adinarayana *et al.*

(2003a) tested several substrates (wheat bran, wheat rawa, bombay rawa, barley, and rice bran) to produce cephalosporin C by *Acremonium chrysogenum* under SSF. Physical and chemical parameters were also optimized. Thus, a maximum productivity of cephalosporin C (22,281 μg/g) was achieved using wheat rawa and soluble starch (1%) and yeast extract (1%) as additives, an incubation period of 5 days, an incubation temperature of 30 °C, an inoculum level of 10%, a ratio of salt solution to weight of wheat bran of 1.5:10, a moisture content of solid substrate of 80% and pH 6.5. Adinarayana *et al*. (2003b) also reported the production of neomycin by *Streptomyces marinensis* under SSF using wheat rawa as a support-substrate. Ellaiah *et al*. (2004) tested several support-substrates (wheat bran, wheat rawa, rice bran, rice rawa, rice husk, rice straw, maize bran, ragi bran, green gram bran, black gram bran, red gram bran, corn flour, jowar flour, sago, and sugar cane bagasse) for neomycin production by a mutant strain of *S. marinensis*, under SSF. The accumulation of neomycin by SSF was 1.85 times higher than the SmF.

Asagbra *et al*. (2005) assessed the ability of *Streptomyces* sp. OXCI, *S. rimosus* NRRL B2659, *S. rimosus* NRRL B2234, *S. alboflavus* NRRL B1273, *S. aureofaciens* NRRL B2183, and *S. vendagensis* ATCC 25507 to produce tetracycline under SSF conditions using peanut shells, corn cob, corn pomace, and cassava peels as substrates. They found that peanut shells were the most effective substrate. Mizumoto *et al*. (2006) reported the production of the lipopeptide antibiotic iturin A by *Bacillus subtilis* using soya bean curd residue, okara, a by-product of tofu manufacture in SSF. After 4 days of incubation, iturin A production reached 3300 mg/kg wet solid material (14 g/kg dry solid content material), which was approximately 10-fold higher than that in SmF.

IV. MULTIFUNCTIONAL FOOD INGREDIENT PRODUCTION FROM FVW

Several research groups have been working on the development of multifunctional ingredients from vegetable residues and its application in different food products. The crude fiber content combined with at least one other property enables them to fulfill several functions in food as depicted by Laufenberg *et al.* (2003).

Operating areas of multifunctional food ingredients due to food properties and quality:

1. Nutritional and healthy quality, for example, vitamin content, dietary fiber content.
2. Food product structure, for example, porosity, network structure.
3. Sensorial properties, for example, texture/structure, mouth feel, freshness.

4. Physical properties, for example, density, viscosity.
5. Processing properties, for example, water binding ability, emulsifying properties.

A couple of quality determining food properties can be governed by the application of these food ingredients. The raw material mostly used is carrot pomace (Filipini and Hogg, 1997; Lucas *et al.*, 1997), followed by citrus waste (Sreenath *et al.*, 1995; Widmer and Montanari, 1995), grape or apple pomace (Masoodi and Chauhan, 1998), sugar beet pomace (Koksel and Ozboy, 1999), orange, mango, and apple peel (Larrauri *et al.*, 1999). New approaches try to use the dietary fibers as a matrix for the encapsulation of antioxidants (Saura-Calixto, 1998) or flavors (Zeller, 1999), using both the physiological effects and the technological advantages in the form of a controlled release.

A. Dietary fibers

A number of researchers have used fruits and vegetable by-products such as apple, pear, orange, peach, blackcurrant, cherry, artichoke, asparagus, onion, carrot pomace (Nawirska and Kwasnievska, 2005; Ng *et al.*, 1999) as sources of dietary fiber supplements in refined food. Dietary fiber concentrates from vegetables showed a high total dietary fiber content and better insoluble/soluble dietary fiber ratios than cereal brans (Grigelmo-Miguel and Martin-Belloso, 1999). The preparation of dietary fibers from food by-products was summarized by Larrauri *et al.* (1999).

Cauliflower has a very high waste index (Kulkarni *et al.*, 2001) and is an excellent source of protein (16.1%), cellulose (16%), and hemicellulose (8%) (Wadhwa *et al.*, 2006). It is considered as a rich source of dietary fiber and it possess both antioxidant and anticarcinogenic properties. Phenolic compounds and vitamin C are the major antioxidants of brassica vegetables, due to their high content and high antioxidant activity (Podsedek, 2007). Lipid-soluble antioxidants (carotenoids and vitamin E) are responsible for up to 20% of the brassica total antioxidant activity. The level of nonstarch polysaccharide (NPS) in the upper cauliflower stem is similar to that of the floret and both are rich in pectic polysaccharides, while the cauliflower lower stem is rich in NPS due mainly to cellulose and xylan deposition (Femenia *et al.*, 1998).

Stojceska *et al.* (2008) studied the incorporation of cauliflower trimmings into ready-to-eat expanded products (snacks) and their effect on the textural and functional properties of extrudates. It was found that addition of cauliflower significantly increased the dietary fiber and levels of proteins. Extrusion cooking significantly ($P < 0.0001$) increased the level of phenolic compounds and antioxidants but significantly ($P < 0.001$) decreased protein *in vitro* digestibility and fiber content in the extruded products. The expansion indices, total cell area of the products, wall thickness showed negative correlation to the level of cauliflower. Sensory test panel indicated that cauliflower could be incorporated into ready-to-eat expanded products up to the level of 10%.

Content and composition of dietary fibers of some residues have been summarized and listed by Laufenberg (2003). The high crude fiber content of the vegetable pomace (in total 20–65% DM) suggests its utilization as a crude fiber ''bread improver.'' In bread and bakery goods, as well as in pastry, cereals, and dairy products, the investigated carrot pomace works as a stabilizer. Besides crude fiber it is rich in provitamins, color, and natural acids. It represents several functional properties as above mentioned, additionally substitutes sourdough in bread, carrot pomace is acidifying agent, preservative, or antioxidant in several food products (Filipini and Hogg, 1997; Masoodi and Chauhan, 1998).

B. Coloring agents and antioxidants

In beverages, carrot pomace, or citrus waste will stabilize the natural color, improve the vitamin and fiber content, enhance the viscosity (mouthfeel) (Laufenberg *et al.*, 1996), and enrich or adjust the cloudy appearance (Sreenath *et al.*, 1995). The organoleptic and chemical properties offer a widespread use in healthy and functional drinks and selected fruit juices.

Olive oil wastewaters are rich in antioxidant compounds, particularly in hydroxytyrosol derivatives (Visioli *et al.*, 1999). Hydroxytyrosol strongly inhibited low-density lipoprotein oxidation stimulated by 2,2′-azobis(2-aminopropane) hydrochloride (Aruoma *et al.*, 1998). Further investigations point out that hydroxytyrosol and oleuropein are potent scavengers of superoxide radicals (Visioli *et al*, 1998). Tyrosol and hydroxytyrosol are dose-dependently absorbed by humans and eliminated as their glucuronide conjugates, indicating a good bioavailability (Visioli *et al.*, 2000).

1. Polyphenolic compounds

Saura-Calixto (1998) produced a dietary fiber rich in associated polyphenolic compounds combining in a single material the physiological effects of both dietary fiber and antioxidants. Fiber matrices could act as support for biocolorants made of anthocyanins from olive cake (Clemente *et al.*, 1997), lycopenes from tomato skins (Al-Wandawi *et al.*, 1985) or β-carotene from carrot pomace. Phenolic compounds are powerful antioxidants and may possess potential pharmacological properties, already widely used with green tea catechins (Nwuha *et al.*, 1999) or ferulic acid extracted from sugar beet pulp (Couteau and Mathaly, 1998) which could make them desirable ingredients in the developing market of ''functional foods'' for health. Bioflavonoids like hesperidin, naringin, or rutin are able to normalize capillary permeability and vascular brittleness, therefore they are frequently called vitamin P factors. Hesperidin is applied in vein medication, acts antiviral in flue therapy, and owns artificial sweetener properties; hydrated naringin is ~300 times sweeter than saccharose, neohesperidin almost 2000 times. Grape skin extract in powder form is commercially available as a natural food coloring agent. Besides the blue–red color the food will be enriched with ''healthy'' polyphenols (Anon, 1999). The fermentation of dietary fibers increases digestibility, shelf life and preserves the bioactivity of the components.

The food and agricultural products processing industries generate substantial quantities of phenolic-rich by-products, which could be valuable natural sources of antioxidants to be employed as ingredients. For example, more than 450,000 ton of onion wastes is produced annually in the European Union, mainly in the United Kingdom, Holland and Spain (Roldan *et al*., 2008). Some of these by-products have been the subject of investigations and have proved to be effective sources of phenolic antioxidants (Balasundram *et al*., 2006). Onion shows a variety of pharmacological effects such as growth inhibition of tumor and microbial cells, reduction of cancer risk, scavenging of free radicals, and protection against cardiovascular disease, which are attributed to specific sulfur-containing compounds and flavonoids (Ly *et al*., 2005). In addition, onions have been found to have antioxidant properties in different *in vitro* models (Kim and Kim, 2006). Recent studies of Roldan *et al*. (2008) have shown that sulfhydryl (SH or thiol) groups are good inhibitors of the enzyme polyphenol oxidase (PPO) (Ding *et al*., 2002). Therefore, it is assumed that the thiol compounds contained in onion might be the active components responsible for the PPO inhibitory effect of onion. Onion extracts could be used as natural food ingredients for the prevention of browning caused by PPO (Kim *et al*., 2005). Onion wastes have been stabilized by thermal treatments—freezing, pasteurization, and sterilization—to evaluate the effect of the processing and stabilization treatment on the bioactive composition, antioxidant activity and PPO enzyme inhibition capacity. Processing of ''Recas'' onion wastes to obtain a paste (mixture content) and applying a mild pasteurization were the best alternatives to obtain an interesting stabilized onion by-product with good antioxidant properties that made useful its use as functional food ingredient.

Grapes are among the world's largest fruit crop with more than 60 million ton produced annually. About 80% of the total crop is used in wine making (Mazza and Miniati, 1993), and pomace represents approximately 20% of the weight of grapes processed. From these data, it can be calculated that grape pomace amounts to more than 9 million ton per year. A great range of products such as ethanol, tartrates, citric acid, grape seed oil, hydrocolloids, and dietary fiber are recovered from grape pomace (Girdhar and Satyanarayana, 2000). Anthocyanins, catechins, flavonol glycosides, phenolic acids and alcohols and stilbenes are the principal phenolic constituents of grape pomace. Anthocyanins have been considered the most valuable components, and methods for their extraction have been reported (Mazza, 1995). In Chardonnay grape pomace, 17 polyphenolic constituents were identified by NMR spectroscopy (Lu & Foo, 1999). Chardonnay pomace was also a source of two unusual dimeric flavanols (Foo *et al.*, 1998). Catechin, epicatechin, epicatechin gallate, and epigallocatechin were the major constitutive units of grape skin tannins (Souquet *et al.*, 1996). A new class of compounds, aminoethylthio- flavan-3-ol conjugates, has been obtained from grape pomace by thiolysis of polymeric proanthocyanidins in the presence of cysteamine (Torres and Bobet, 2001). Grape seeds are rich sources of polyphenolics, especially of procyanidins, which have been shown to act as strong antioxidants and exert health-promoting effects (Jayaprakasha *et al.*, 2001). Addition of supplementary quantities of grape seeds to grape juice increased catechin and procyanidin contents of wines (Kovac *et al.*, 1995).

2. Coloring agents

More than 200,000 ton of red beet are produced in Western Europe annually, most of which (90%) is consumed as vegetable. The remainder is processed into juice, coloring foodstuff and food colorant, the latter commonly known as beetroot red (Henry, 1996). Though still rich in betalains, the pomace from the juice industry accounting for 15–30% of the raw material (Schieber *et al.*, 2001) is disposed as feed or manure. The colored portion of the beetroot ranges from 0.4 to 2.0% of the dry matter, depending on intraspecific variability, edaphic factors, and postharvest treatments. Beets are ranked among the 10 most potent vegetables with respect to antioxidant capacity ascribed to a total phenolic content of 50–60 mmol/g dry weight (Vinson *et al.*, 1998). A more recent investigation showed that total phenolics decreased in the order peel (50%), crown (37%), and flesh (13%). Epidermal and subepidermal tissues, that is, the peel, also carried the main portion of betalains with up to 54%, being lower in crown (32%) and flesh (14%). Whereas the colored fraction consisted of betacyanins and betaxanthins, the phenolic portion of the peel showed ltryptophane, p-coumaric and ferulic acids, as well as cyclodopa glucoside derivatives (Kujala *et al.*, 2001). Toxicological studies revealed that betanin, the major compound from red beet, did not exert allergic potential, nor mutagenic or hepatocarcinogenic effects. High content in folic acid amounting to 15.8 mg/g dry matter is another nutritional feature of beets (Wang and Goldman, 1997).

C. Gelation properties

Pectic substances have an important influence on food texture and are used in products like jams, jellies, dairy products, beverages, pastries, and confectioneries. More and more they are used in pharmaceutics and cosmetics as well. Pectin is located in the cell walls of vegetables and fruits; the use of residual matter as a potential pectin source is commercially and environmentally interesting. Pectin is heterogeneous complex polysaccharide. All pectin molecules contain linear segments of (1 → 4)-linked α-D-galacto-pyranosyluronic acid units with some of the carboxyl groups esterified with methanol. The gelation mechanism of pectins is mainly governed by their degree of esterification (DE). Commonly, two types of pectin gels are distinguished. The first type made from high methoxyl pectins (DE beyond 50%) form gels in an acidic environment and in the presence of sucrose. The second type of pectin gel is composed of low methoxyl pectins (DE below 50%). These pectins form gels in presence of a divalent metal ions, for example, calcium ions. In both cases, gelation and gel properties depend on many factors, including pH, temperature, DE, sugar, Calcium ions, and pectin content.

Apple pomace is a natural source of pectic substances, being an important raw material for pectin production throughout the world, it contains 10–15% of pectin on a dry matter basis (Vendruscolo *et al.*, 2008). In apple pomace, the pectin is mainly present as protopectin, an acid-soluble polysaccharide. Canteri-Schemin *et al.* (2005) studied the effects of particle size, apple variety, and type of acid on the extraction of pectin from apple pomace. The authors found that higher extraction yields (around 14%) were obtained when pomace particles larger than 106 μm and smaller than 250 μm were used. Marcon *et al.* (2005), using an experimental design, found that the best yield of pectin extraction from apple pomace (16.8% wt/wt) was obtained with higher temperatures (100 °C, 80 min). Wang *et al.* (2007) studied the applicability of microwave-assisted extraction to obtain pectin from apple pomace. They studied the effect of four different factors (extraction time, pH of acid solution, solid:liquid ratio, and microwave power) on the pectin yield. An extraction time of 20.8 min, pH 1.01, solid:liquid ratio of 0.069, and a microwave power of 499.4 W produced the highest extraction yield (0.315 g per 2 g of dried apple pomace). According to the authors, these process conditions allowed an important reduction in the time required for pectin extraction. The presence of up to 30% pectin in a dry residual matter basis like sugar beet pulp, carrot pomace, potato pulp, or lemon peel and its availability in large quantities have made extraction worthwhile.

D. Oil and meal

Goldenberry pomace (seeds and skins) represents the waste obtained during juice processing (around 27.4% of fruit weight). In the present contribution, the potential of goldenberry pomace for use as a substrate for the production of edible oil was evaluated (Ramadan *et al.*, 2008). Toward developing goldenberry as a commercial crop, the results provide important data for the industrial application of goldenberry. Three extraction methods were checked for the best oil yield. The *n*-hexane-extractable oil (expressed as SE) content of the raw by-products was estimated to be 19.3%. Enzymatic treatment with pectinases and cellulases followed by centrifugation in aqueous system (expressed as EAE enzyme–aqueous–extract) or followed by solvent extraction (expressed as ESE enzyme–solvent–extract) was also investigated for recovery of oil from pomace fruit. Enzymatic hydrolysis of pomace followed by extraction with *n*-hexane reduced the extraction time and enhanced oil extractability up to a maximum of around 7.60%. Moreover, enzymation followed by solvent extraction increased the levels of protein, carbohydrates, fiber, and ash in the remaining meal. The study covers also the chemical composition and some fractional properties of different pomace extracts (EAE, SE, and ESE). Concerning the oil composition, there were relatively no changes noted in the fatty acid pattern of the oils extracted with different techniques. As a first step toward developing goldenberry as a commercial crop, the data obtained will be useful as an indication of the potentially economical utility of goldenberry pomace as a source of edible oil and functional products. Although goldenberry is a part of a supplemental diet in many parts of the world and its consumption is becoming increasingly popular also in the nonproducer countries, information on the phytochemicals in this fruit is limited. Yet these phytochemicals may bring nutraceutical and functional benefits to food systems. A variety of health-promoting products improved from goldenberry pomace may include ground dried skins and extracts obtained from skins and/or seeds. The levels of polar lipids, unsaponifiables, peroxides, and phenolics in different extracts were associated with oxidative stability and radical scavenging activity.

E. Food preservation

Evaluation of olive- and grape-based natural extracts as potential preservatives for food was carried out by Serra *et al.* (2008). The antimicrobial activities of two waste-derived extracts, from olive oil and wine production, both rich in polyphenols, and three standard well recognized antioxidants (quercetin, hydroxytyrosol, and oleuropein) were investigated against five microbial species (*Escherichia coli, Salmonella poona, Bacillus* *cereus*, *S. cerevisiae*, and *Candida albicans)*. The tests were carried out using a microplate photometer assay. The results obtained suggest that the natural extracts may have important applications in the future as natural antimicrobial agents for food industry as well as for medical use. The natural extracts showed more antimicrobial activity than shown by the selected antioxidants alone against all microorganisms.

F. Production of biopolymers, films, food packaging

Increasing interest in high-quality food products with increased shelf life and reduced environmental impact has encouraged the study and development of edible and/or biodegradable polymer films and coatings. Edible films provide the opportunity to effectively control mass transfer among different components in a food or between the food and its surrounding environment. Materials used to produce edible films can be divided into four categories: biopolymer hydrocolloids, lipids, resins, and composites. Biopolymer hydrocolloids include proteins such as gelatin, keratin, collagen, casein, soy protein, whey protein, myofibrillar proteins, wheat gluten, and corn zein; and polysaccharides such as starch, starch derivatives, cellulose derivatives, and plant gums. Suitable lipids include waxes, acylglycerols, and fatty acids. Resins include shellac and wood rosin. Composites generally contain both lipid and hydrocolloid components in the form of a bilayer or an emulsion (Perez-Gago and Krochta, 2005). Proteins such as wheat gluten, corn zein, soy protein, myofibrillar proteins, and whey proteins have been successfully formed into films using thermoplastic processes such as compression molding and extrusion. Thermoplastic processing can result in a highly efficient manufacturing method with commercial potential for large-scale production of edible films due to the low moisture levels, high temperatures, and short times used. Addition of water, glycerol, sorbitol, sucrose, and other plasticizers allows the proteins to undergo the glass transition and facilitates deformation and processability without thermal degradation. Target film variables, important in predicting biopackage performance under various conditions, include mechanical, thermal, barrier, and microstructural properties. Film applications include their use as wraps, pouches, bags, casings, and sachets to protect foods, reduce waste, and improve package recyclability (Hernandez-Izquierdo and Krochta, 2008).

G. Derivatives of meat wastes

Collagen, a by-product of meat production, finds only little use in the production of food for its low nutritional value and deficit in essential amino acids (Langmaier *et al*., 2008). At present, the principal field of its industrial use is in the production of leather—a natural product widely used for clothing, footwear, and fancy goods manufacture. An important field also is the manufacture of edible (biodegradable) meat product casings, which, due to the preserved fibrous structure of collagen, display excellent mechanical characteristics (Osburn, 2002). A minor use in terms of volume, but not in significance, is the application in human medicine (tissue bio-engineering—vascular prostheses, membranes, transport systems for antibiotics, steroids and other drugs, implant matrices, haemostatic foams, burn dressings, etc.). A detailed survey of such recent applications was given by Lee *et al.* (2001).

In packaging technology, films or foils obtained from protein hydrogels have the advantage of a high barrier capacity for oxygen (oxidation of packed materials, especially of lipoid character), carbon dioxide (important in packaging and preserving fruit and vegetables) and aromatic substances (spices and other ingredients of semifinished food products). Their hydrophilic character, on the other hand, limits their barrier capacity for humidity (water vapor), mostly accompanied by their solubility in water. Mechanical strength and elongation are somewhat lower when compared with similar packages based on synthetic polymers, whereas, fragility is higher. These characteristics may be controlled by adding suitable plasticizers, which, however, usually further increase the hydrophilic character of plasticized films. The hydrophilic character of proteinic films and foils can be best controlled by increasing the cross-link density attainable through cross-linking reactions by specific enzymes—peroxidase from horseradish, amino-transferases of bacterial origin—*Streptoverticilium* sp., *Streptomyces* sp., and others: (Carvalho de and Grosso, 2004; Henning and van Nostrum, 2002), or aldehydes, most often formaldehyde, glyoxal, or glutaraldehyde (Bigi *et al.*, 2001). A suitable degree of cross-linking enables the control of the rate of dissolving of film (foil) and thus also the rate of releasing active component from such packages. This is of significance for maintaining the required concentration of active substance—for example, drugs in the bloodstream, or farming chemicals (fertilizers, insecticides, pesticides, and others) in soil or in other environments.

Enzymatic hydrolyzates of waste collagen proteins (H), from current industrial manufacture (leather, edible meat product casings, etc.) of mean molecular mass 20–30 kDa by a reaction with dialdehyde starch (DAS), produces hydrogels applicable as biodegradable (or even edible) packaging materials for food, cosmetic, and pharmaceutical products. Thermo-reversibility of prepared hydrogels is given by concentrations of H and DAS in a reaction mixture. At concentrations of H 25–30% (w/w) and that of DAS 15–20% (related to weight of hydrolyzate), thermo-reversible hydrogels arise, which can be processed into packaging materials by a technique similar to that of soft gelatin capsules (SGC). Exceeding the limit of 20% DAS leads to hydrogels that are thermo-reversible only in part, a further increase in DAS concentration then leads to thermo-irreversible gels whose processing into biodegradable packaging materials necessitates employment of other procedures. Thus, better utilization of collagen raw material is achieved, and ecologically unfavorable impacts of the collagen-processing industry are reduced, namely ammonia pollution of wastewaters and the inevitable disposal of solid, unprocessed collagen waste in landfills (Langmaier *et al*., 2008).

H. Derivatives of seafood wastes

1. Production of carotenoids

Enzymatic isolation of carotenoid–protein complex from shrimp head waste was carried out by Babu *et al.* (2008). The carotenoids extracted gave maximum yield over the traditional, solvent extraction process, and SC–CO_2 extraction. Trypsin recovered highest amount of carotenoids from all types of head wastes, but pepsin and papain also showed good recoveries of carotenoids. The percent of recovery varied with the raw materials and the trend was *Penaeus indicus* > *Penaeus monodon* (culture) > *Metapenaeus monocerous* > *Penaeus monodon* (wild). The loss of carotenoids during processing of frozen carotenoid–protein cake (CPC) to freeze-dried product was noticed in all trials. Astaxanthin was the main stable pigment and its proportion in total carotenoids increased in freeze-dried product with the loss of minor carotenoids such as β-carotene and their derivatives. The predominance of astaxanthin in the carotenoids indicates that the both frozen CPC and freeze-dried CPC are good source of natural antioxidant and also natural carotenoids.

2. Production of glucosamine and carboxymethylchitin

Shrimp shell waste can be economically converted to chitin, a mucopolysaccharide (Santhosh and Mathew, 2008). This marine polysaccharide and its derivatives hold a major part in our lives as medicines, cosmetics, textiles, paper, food, and other branches of industry because of their unique nature in properties such as low toxicity, biocompatibility, hydrophobicity, etc. Hydrolysis of chitin yields a value added product, glucosamine. Carboxymethylchitin is another derivative of chitin, prepared by the carboxymethylation reaction.

Glucosamine is the natural component of glycoproteins found in connective tissues and gastrointestinal mucosal membranes. This monosaccharide is involved in the formation of nails, tendons, skin, eyes, bones, ligaments, and heart valves. It also plays a role in the mucus secretions of the respiratory and urinary tracts. It is incorporated in the biosynthesis of glycosaminoglycans and proteoglycans, which are essential for the extracellular matrix of connective tissues. Several clinical studies have been reported that glucosamine works better in reducing the symptoms of osteoarthritis. Glucosamine inhibits the cartilage-destructive enzyme collagenase. Glucosamine helps in the synthesis of cartilage by increasing key components of cartilage such as glycosaminoglycans. Various reports confirmed that diabetes patients could also consume glucosamine, which will not increase blood glucose level. Glucosamine appears to undergo a significant first-pass effect in the liver, which metabolizes a significant proportion of the dose to CO_2, water, and urea.

Carboxymethylchitin is having profound versatile applications. Carboxymethylchitin is popularly used in cosmetic products as smoothener, moisturizer, cleaner for face skin conditioning, and cell activator. Carboxymethylchitin is extensively used in wound dressing. For wound dressing, this polymer must be cross-linked to prolong its dimensional integrity during use. One important characteristic feature of carboxymethylchitin is that it is soluble not only in acid media but at any pH range. This unique property makes carboxymethylchitin different from other derivatives of chitin. Solubility of carboxymethylchitin at any pH makes it advantageous to use in food products and cosmetics. Carboxymethylchitin is used to preserve fruits also.

3. Production of gelatin

The amount of gelatin used in the worldwide food industry is increasing annually (Montero and Gomez-Guillen, 2000). The estimated world usage of gelatin is 200,000 MT/year (Badii & Howell, 2005). Generally, gelatin is commercially made from skins and skeletons of bovine and porcine by alkaline or acidic extraction. However, the occurrences of bovine spongiform encephalopathy and foot/mouth diseases have led to the major concern of human health. Thus by-products of mammalians are limited for production of collagen and gelatin as the functional food, cosmetic, and pharmaceutical products (Cho *et al.,* 2005). Studies on extraction and functional properties of gelatin from fish by-products, such as skin and bone, have been reported (Choi and Regenstein, 2000; Fernandez-Dıaz *et al.,* 2001). Gelatin was extracted from precooked tuna caudal fin with the yield of 1.99% (Aewsiri *et al.,* 2008). Tuna fin gelatin (TFG) contained high protein content (89.54%) with hydroxyproline content of 14.12 mg/g. TFG comprised a lower content of high-molecular-weight cross-links and hydroxyproline content than porcine skin gelatin (PSG). However, proline content in TFG was twofold higher than that of PSG. The highest bloom strength and turbidity of TFG were observed at pH 6, while the lowest solubility was noticeable at the same pH. The bloom strength of TFG gel was lower than that of PSG gel at all pHs. TFG exhibited the lower emulsifying activity but greater emulsifying stability than PSG ($P < 0.05$). TFG showed poor foaming properties than PSG. The tensile strength, elongation at break, water vapor permeability of film from PSG was greater than those of TFG ($P < 0.05$). The study revealed that gelatin of good quality can be prepared from tuna processing discards.

4. Production of marine peptone

A diverse group of peptones obtained by enzymatic hydrolysis of wastewater from the industrial processing of octopus showed their effectiveness to promote the growth of lactic acid bacteria (LAB) and the production of bacteriocins. The highest nisin formation by *L. lactis* was reached using peptones from papain hydrolysis for 24 h (enzyme concentration: 1.25 mg papain/g protein). On the other hand, the highest pediocin production by *Pediococcus acidilactici* was obtained with peptones derived from 4 h of pepsin digestion (enzyme concentration: 3.75 mg papain/g protein). Thus, these marine peptones are promising alternatives to currently available and expensive commercial medium as well as a possible solution to valorize this problematic wastewater (Vazquez and Murado, 2008; Vazquez *et al*., 2004).

From the viewpoint of their industrial importance, LAB are classified as one of the greatest and most important microbial groups due to their significant role in food fermentation and preservation, as a natural microflora or as an inoculum added under controlled process conditions. Among the molecules produced by these microorganisms which present antimicrobial activity are lactic and acetic acid, ethanol, diacetyl, 2,3-butanediol, and bacteriocins. Bacteriocins produced by LAB are peptides with antimicrobial activity and have great importance to the food industry, as they are innocuous, sensitive to digestive proteases of vertebrates, and do not change the organoleptic properties of the food. LAB and, specifically, bacteriocins productions are very fastidious due to the need for rich growth media containing nutrients such as carbohydrates, nucleic acids, minerals, vitamins and, mainly, amino acids, proteins, or protein hydrolyzates. For example, the standard laboratory media (MRS, TGE, APT) solve the problem of protein sources, incorporating products such as bactopeptone, tryptone, meat extract, or yeast extract (sometimes all of these) on formulations which reach expensive costs. The use of low-cost proteins or protein fractions will bring about a reduction in large-scale production costs. Furthermore, when food waste is used to obtain these nutritional sources (e.g., waste generated by industries which process foodstuffs of marine origin), a complete productive cycle is closed: the recycling and valorization of pollutant waste and the obtaining of a product of high added value, used for control and preservation of foodstuffs (LAB and bacteriocins).

V. VEGETABLE RESIDUES AS BIOADSORBENTS FOR WASTEWATER TREATMENT

Conventional methods for treating wastewater containing dyes, aromatic compounds, or heavy metals are coagulation, flocculation, reverse osmosis, nanofiltration and pervaporation (Paul and Ohlrogge, 1998), and activated carbon adsorption, the latter of which is combined with membrane processes like nanofiltration (Eilers and Melin, 1999) or ultrafiltration (Lenggenhager and Lyndon, 1997).

Additional efforts are focused on the creation of ''bioadsorbents'' with improved functionality, using their natural content of adsorptive components or enhancing their adsorption rate by combination of favored raw materials. A number of low-cost adsorbents have been tried for wastewater treatment like wool fibers (Balkose and Baltacioglu, 1992), microbial biosorbents (Xie *et al.*, 1996), pillared clays (Baksh *et al.*, 1992), coir pith untreated (Namasivayam and Kadirvelu, 1996) or activated carbon (Namasivayam and Kadirvelu, 1997), banana pith (Namasivayam and Kanchana, 1992), orange peel (Namasivayam *et al.*, 1996), peanut and walnut shells (Randall *et al.*, 1975), modified onion skin (Bankar and Dara, 1982), corncobs (Tsai *et al.*, 1998), the combination of onion skin with corncobs (Odozi and Emelike, 1985), peanut skin (Randall *et al.*, 1975), palm kernel husk (Omgbu and Iweanya, 1990), pecan (Ahmenda *et al.*, 2000a,b) and almond shells (Toles *et al.*, 2000), or functionalized lignin extracted from sugarcane bagasse (Peternele *et al.*, 1999). Suitable is even black currant and apple dietary fiber because of its binding capacity for cadmium and lead (Borycka and Zuchowski, 1998). The pretreatment methods for these materials differ, reaching from chemical extraction of lignin (Peternele *et al.*, 1999) to adding chemicals and further pyrolysis (Ahmenda *et al.*, 2000a,b; Toles *et al.*, 2000), from polymerization (Bankar and Dara, 1982) to just cutting, drying, and grinding (Namasivayam *et al.*, 1996).

A. Biosorption of metal ions

Biosorption can be used as a cost-effective and efficient technique for the removal of toxic heavy metals from wastewater. Toles *et al.* (2000) investigated the adsorptive properties of air-activated almond shells toward several organics and copper. The almond shell carbon could remove more than 400% of Cu^{2+} from the solution compared to commercial carbon Norite RO3515. The organic adsorption of almond shell carbon was lower compared to Filtrasorbe 400, ranging between 84% and 92% of the Calgone carbon total adsorption. Convincing as well is the cost estimation: commercial carbons are produced for US $3.30 1/kg, almond shell carbons for US $2.45 1/kg. Johns *et al.* (1998) compared seven commercial granulated activated carbons (GAC) with GACs made of residual matter like almond shells, oil palm shells, sugarcane bagasse, rice straw, soybean hull, peanut, and walnut shells. Both CO_2 and steam activated nutshell carbons consistently removed more total organics than the commercial GACs. The soybean hull-based GACs showed three or four times higher copper adsorption compared with all other commercial or coproduct-based GACs. Effective adsorption is as well feasible without physical or chemical activation. The raw material has only been cut, dried, and ground before the experiments. Laufenberg *et al*. (2003) reviewed the most important influencing adsorption parameters, for example, residue combinations and synergies, particle size, adsorbent dosage, removed component and its initial concentration, agitation time and contact time, pH-value, surface area, targeted metabolism, binding mechanisms, bioreactor design used as well as posttreatment procedure. The most appropriate bioreactor design is a packed bed column, as adsorption is much more effective in a packed bed than in a stirred tank bioreactor. A packed bed will permit faster mass transfer and higher conversion, assuming that a large volume of solution is to be fed through a small bed of adsorbing solid. The bed is completely uniformly packed and the flow moving evenly, without dispersion and independent of the bed's radius. Hence in the packed bed the concentration in the solid is in equilibrium with the high feed concentration. In stirred tank loaded solid reaches equilibrium with depleted solution which is less than with the feed solution. Therefore, yields are much less effective (Cussler, 1997).

In recent years, attention has been focused on the utilization of unmodified or modified rice husk as a sorbent for the removal of pollutants. Rice husk is the outer covering of paddy and accounts for 20–25% of its weight. It is removed during rice milling and is used mainly as fuel generating CO_2 and other forms of pollution to the environment. The annual generation of rice husk in India is in the range of 18–22 million ton. Unmodified rice husk has been evaluated for their ability to bind metal ions. Various modifications on rice husk have been reported to enhance sorption capacities for metal ions and other pollutants (Kumar and Bandyopadhyay, 2006). Mohan and Sreelakshmi (2008) reported the results of the study on the performance of low-cost adsorbent such as raw rice husk (RRH) and phosphate-treated rice husk (PRH) in removing the heavy metals such as lead, copper, zinc, and manganese. The adsorbent materials adopted were found to be an efficient media for the removal of heavy metals in continuous mode using fixed bed column. The column studies were conducted with 10 mg/L of individual and combined metal solution with a flow rate of 20 ml/min with different bed depths such as 10, 20, and 30 cm. The breakthrough time was also found to increase from 1.3 to 3.5 h for Pb (II), 4.0–9.0 h for Cu(II), 12.5–25.4 h for Zn (II), and 3.0 to 11.3 h for Mn (II) with increase in bed height from 10 to 30 cm for PRH.

Different column design parameters like depth of exchange zone, adsorption rate, adsorption capacity, and so on were calculated. It was found that the adsorption capacity and adsorption rate constant were increased and the minimum column bed depth required was reduced when the rice husk is treated with phosphate, when compared with that of RRH.

Orange waste, produced during juicing has been loaded with zirconium(IV) so as to examine its adsorption behavior for both As (V) and As (III) from an aquatic environment. Immobilization of zirconium onto the orange waste creates a very good adsorbent for arsenic. Adsorption kinetics of As (V) at different concentrations are well described in terms of pseudo-second-order rate equation with respect to adsorption capacity and correlation coefficients. Arsenate was strongly adsorbed in the pH range from 2 to 6, while arsenite was strongly adsorbed between pH 9 and 10. Moreover, equimolar (0.27 mM) addition of other anionic species such as chloride, carbonate, and sulfate had no influence on the adsorption of arsenate and arsenite. The maximum adsorption capacity of the Zr(IV)-loaded onto a saponified orange waste (SOW) gel was evaluated as 88 and 130 mg/g for As(V) and As(III), respectively. Column adsorption tests suggested that complete removal of arsenic was achievable at up to 120 Bed Volumes (BV) for As (V) and 80 BV for As (III). Elution of both arsenate and arsenite was accomplished using 1 M NaOH without any leakage of the loaded zirconium. Thus this efficient and abundant bio-waste was successfully employed by Biswas *et al.* (2008) for the remediation of an aquatic environment polluted with arsenic.

Microbial biomass, such as fungi, would be particularly cost-effective as there are many food-processing plants in both Turkey and the United States, and many other countries that could provide wastewater as substrate at a very low cost for the cultivation of these. Dried biomass of *Rhizopus oligosporus* produced using wet milling corn-processing wastewater as organic substrate was used as an adsorbent for Copper ions in water. The adsorption process was carried out in a batch process and the effects of contact time (1–48 h), initial pH (2.0–6.0), initial metal ion concentration (20–100 mg/L), and temperature (20–38 °C) on the adsorption were investigated by Ozsoy *et al.* (2008). Experimental results showed that the maximum adsorption capacity was achieved at pH 5.0, and adsorbed Cu(II) ion concentration was increased with increasing initial metal concentration and contact time. The isothermal data could be described well by the Langmuir equations and monolayer capacity had a mean value of 79.37 mg/g. A pseudo-second-order reaction model provided the best description of the data with a correlation coefficient 0.99 for different initial metal concentrations. Thermodynamic parameters indicated that biosorption of Cu(II) on *R. oligosporus* dried biomass was exothermic and spontaneous. The results of FTIR analyses indicated that amide I and hydroxyl groups of adsorbent played important role in binding Cu (II).

Schiewer and Patil (2008) investigated the removal of cadmium by fruit wastes (derived from several citrus fruits, apples, and grapes). Citrus peels were identified as the most promising biosorbent due to high metal uptake in conjunction with physical stability. Uptake was rapid with equilibrium reached after 30–80 min depending on the particle size (0.18–0.9 mm). Sorption kinetics followed a second-order model. Sorption equilibrium isotherms could be described by the Langmuir model in some cases, whereas in others an S-shaped isotherm was observed, that did not follow the Langmuir isotherm model. The metal uptake increased with pH, with uptake capacities ranging between 0.5 and 0.9 meq/g of dry peel. Due to their low cost, good uptake capacity, and rapid kinetics, citrus peels are a promising biosorbent material warranting further study.

B. Adsorption of dyes from wastewater

The wastewaters discharged from dyeing processes exhibit low BOD, high COD, are highly colored, hot and alkaline, containing high amounts of dissolved solids. There is a wide range of pH, making conventional biological and chemical treatment processes difficult (Lee, *et al.*, 1999). The dyes are highly colored polymers and have low biodegradability. The disposal of colored wastes is undesirable because of their toxicity to aquatic life and carcinogenicity.

While cassava is an important crop across a wide range of tropical environment, cassava peels are an agricultural waste from the food-processing industry. Activated carbon prepared from cassava peel was used as an adsorbent in removal of dyes and metal ions from aqueous solutions. The material impregnated with H_3PO_4 showed higher efficiency than the heat-treated material (Rajeshvarisivaraj *et al.*, 2001).

Tsai *et al.* (2008) proved feasibility to utilize the food-processing waste for removing dye from the industrial dying wastewater. The beer brewery waste has been shown to be a low-cost adsorbent for the removal of basic dye from the aqueous solution as compared to its precursor (i.e., diatomite) based on its physical and chemical characterizations including surface area, pore volume, scanning electron microscopy, and nonmineral elemental analyses. The pore properties of this waste were significantly larger than those of its raw material, reflecting that the trapped organic matrices contained in the waste probably provided additional adsorption sites and/or adsorption area. The results of preliminary adsorption kinetics showed that the diatomite waste could be directly used as a potential adsorbent for removal of methylene blue on the basis of its adsorption–biosorption mechanisms. The adsorption parameters thus obtained from the pseudo-second-order model were in accordance with their pore properties. From the results of adsorption isotherm at 298 K and the applicability examinations in treating industrial wastewater containing basic dye, it was further found that the adsorption capacities of diatomite waste were superior to those of diatomite, which were also in good agreement with their corresponding physical properties.

VI. USING EGGSHELL

Large quantities of eggshell waste are discarded in the food-processing industry. Freire *et al.* (2008) investigated the incorporation of eggshell waste as a raw material into a wall tile body, replacing natural carbonate material by up to 15 wt%. Formulations containing eggshell were uniaxially dry pressed and fired at 1150 °C using a fast firing cycle. Physico-mechanical properties of the fired tiles (e.g., linear shrinkage, water absorption, apparent density, flexural strength) were then determined. Development of the microstructure was followed by scanning electron microscope (SEM) and X-ray diffraction (XRD) analyses. The results showed that eggshell waste could be used in wall tiles, in the range 5–10 wt%, as a partial replacement for traditional carbonate-based materials with only a slight decrease in the end product properties.

VII. ADDED-VALUE PRODUCTS FROM WHEY

Much of the material generated as wastes by the dairy industries throughout Europe contains components that could be utilized as substrates and nutrients in a variety of microbial/enzymic processes, to give rise to added-value products. Varieties of processes exist that do this worldwide, some having operated for many years. Joshi (2002) and Marwaha and Arora (2000) are two examples of extensive discussions of current industrial exploitation and future possibilities within this area. Added-value products, actually produced from dairy industry wastes, include animal feed, single-cell protein and other fermented edible products, baker's yeast, organic acids, amino acids, enzymes (e.g., lipases, amylases, cellulases), flavors and pigments, the bio-preservative bacteriocin (from the culture of *L. lactis* on cheese whey) and microbial gums and polysaccharides (Joshi, 2002). A good example of a waste that has received considerable attention as a source of added-value products is cheese whey, which in itself contains many nutrients. Marwaha and Arora (2000) have tracked the products currently produced from whey, and the main destinations of unutilized whey for disposal, summarized in Table 3.7.

Recently, demand for whey started to increase with news of the benefits that the high-quality proteins found in whey provide children, adults, and the elderly. Increased pharmaceutical applications of protein fractions for the control of blood pressure and for inducing sleep might

TABLE 3.7 Whey Utilization or disposal (Marwaha and Arora, 2000)

Processing scheme	Added-value product	Pollutant
Condensed + Dry whole whey	Human food	
	Animal feed	
Demineralized whey	Baby food	
Refined lactose	Edible lactose	
	Animal feed	
Ultrafiltration: Whey protein concentrate	Edible protein	
Ultrafiltration: whey permeate	Refined lactose	Disposed as waste (see below)
	Lactose-hydrolyzed products	
	Fermentation products	
Unutilized whey: for disposal		Disposal on land
		Into inland surface water
		Into a common sewer
		U/F Whey permeate disposed of as waste

further enlarge the market. *The World Market for Whey and Lactose Products 2006–2010—From commodities to value-added ingredients* clearly demonstrates how whey continues to show significant growth rate both in volume terms and particularly in value terms. There has been a significant increase in consumer products launches containing Whey Protein Concentrate from 2001–2003 to 2004–2006 corresponding to approx. 60%. Peters (2005) evaluated economic consequences of the cheese making process trough several example calculations concerning processing of whey in relation to cheese making throughput and several whey processing alternatives. All value-added enhancements by conversion of whey into whey protein concentrates create a larger stream of an aqueous lactose fraction, with the exception of lactoferrin extraction. This means that the high price which can be obtained for whey protein isolate products has to take into account the large quantity of lactose permeate that will necessarily be created in parallel. The most beneficial step in increasing value for whey products would be to add more value to the lactose fraction. The production of galacto-oligosaccharides for the displacement of antibiotics in animal feeding is promising to influence the lactose market. It was calculated that the price of edible lactose has a greater influence on the economics than the price of whey protein.

One example of whey utilization technologies is the production of alcohol from cheese whey at the Carbery Milk Products Ltd. factory, Ballineen, Ireland. The Carberry plant produces 2.59% v/v of ethanol from 4.7 w/v of lactose in whey permeate (Barry, 1982). Because the *Kluveromyces* species, used in anaerobic fermentations, have low ethanol tolerance, preconcentration of the lactose is not possible, so fermentation and distillation costs are considerable. Under Irish conditions potable alcohol is the most profitable outlet but in other countries, anhydrous alcohol for industrial or power uses may be more attractive (Ozmihci and Kargi, 2008).

VIII. FOOD WASTE TREATMENT

Technologies for treatment of aqueous food industry waste streams:

Reduction of BOD and COD is one of the most pressing tasks for a process treating wastes such as those discussed above. Traditional bioconversion technologies for achieving that aim are essentially those developed for sewage treatment and are used widely. They include:

(a) Aerobic processes, such as the activated sludge process (*including Deep Shaft*) and trickling filters (*and other biofilm-based designs*). Here, flocs or films of microorganisms act as adsorption points and powerful oxidizing catalysts that convert organic materials essentially to carbon dioxide and more biomass. When operated continuously, a retention time of approximately 15 days is common.
(b) Anaerobic processes, such as various designs of the anaerobic digester. In these processes, organic material is converted to methane and carbon dioxide (*''biogas''*) and a biomass sludge.

A. Bioprocessing of FVWs

1. Anaerobic digestion

Among the several processes that are being used nowadays for treatment of FVW, the ones described are the following: anaerobic digestion, anaerobic co-digestion, and biodiesel production. Anaerobic digestion converts biomass waste to biogas and compost using bacteria in the absence of oxygen. The biogas is mainly a mixture of CO_2 and CH_4. The biogas is partly utilized to heat the digestion reactors. The rest can be used to generate electricity and/or heat (e.g., with a gas engine) or, after treatment, be fed into the natural gas grid. The biomethanation of FVW is accomplished by series of biochemical transformations, which can be roughly separated in four metabolic stages (Bouallagui *et al.*, 2005) (Fig. 3.4).

Usually, the choice of a temperature range for anaerobic digestion is strictly dependent on the bioclimatic conditions. In Sweden, for example, research is currently undertaken for a possible anaerobic digestion under low-temperature conditions. In the United States, anaerobic digestion of sludge under thermophilic conditions has been abandoned, although it is well established in Europe, especially for the treatment of the organic fraction of municipal solid waste (OF-MSW) (Ahring *et al.*, 2002). In tropical countries, like in Tunisia, where the ambient temperature is higher than 25 °C during a period of more than 8 months in a year, thermophilic anaerobic digestion is readily applicable. Bouallagui *et al.* (2004) compared the performance of anaerobic digestion of FVW in the thermophilic (55 °C) process with those under psychrophilic (20 °C) and mesophilic (35 °C) conditions in a tubular anaerobic digester on a laboratory scale. The aim of this study was to examine the effect of temperature on the anaerobic digestion of FVWs for several retention times and feed concentrations and to compare the energy balance of the process under

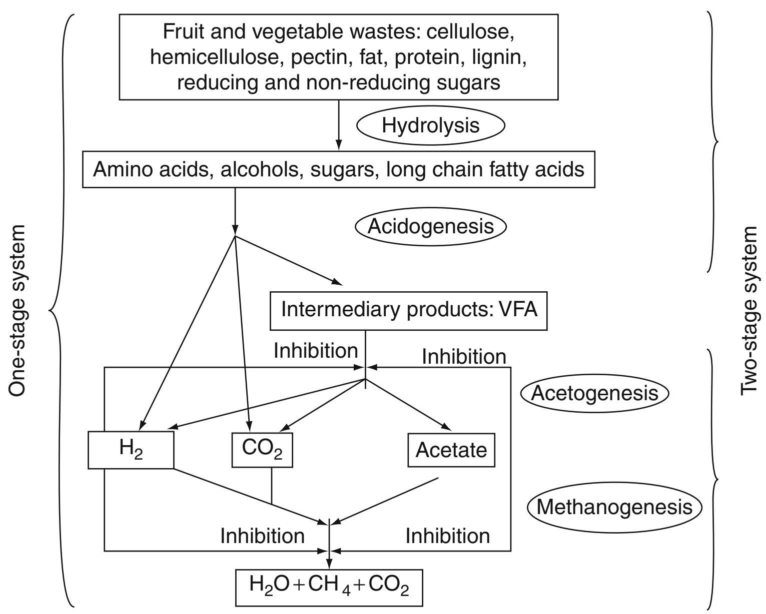

FIGURE 3.4 Reaction scheme for anaerobic digestion of particulate organic material of FVW (Bouallagui *et al.*, 2005).

psychrophilic, mesophilic, and thermophilic conditions. The hydraulic retention time (HRT) ranged from 10 to 20 days, and raw FVW was supplied in a semicontinuous mode at various concentrations of TSs (4, 6, 8, and 10% on dry weight). Biogas production from the experimental thermophilic digester was higher on average than from psychrophilic and mesophilic digesters by 144% and 41%, respectively. The net energy production in the thermophilic digester was 195.7 and 49.07 kJ/day higher than that for the psychrophilic and mesophilic digesters, respectively. The relation between the daily production of biogas and the temperature indicates that for the same produced quantity of biogas, the size of the thermophilic digester can be reduced with regard to that of the psychrophilic and the mesophilic digesters.

Bouallagui *et al*. (2005) reviewed the potential of anaerobic digestion for material recovery and energy production from FVW containing 8–18% TSs, with a total VSs content of 86–92%. The organic fraction includes about 75% easy biodegradable matter (sugars and hemicellulose), 9% cellulose, and 5% lignin. Anaerobic digestion of FVW was studied under different operating conditions using different types of bioreactors. It permits the conversion of 70–95% of organic matter to methane, with a volumetric OLR of 1–6.8 g VS/L day. A major limitation of anaerobic digestion of FVW is a rapid acidification of these wastes decreasing the pH in the reactor, and a larger volatile fatty acids (VFAs) production, which stress and inhibit the activity of methanogenic bacteria. Continuous two-phase systems appear as more highly efficient technologies for anaerobic digestion of FVW. Their greatest advantage lies in the buffering of the OLR taking place in the first stage, allowing a more constant feeding rate of the methanogenic second stage. Using a two-stage system involving a thermophilic liquefaction reactor and a mesophilic anaerobic filter, over 95% volatile solids were converted to methane at a volumetric loading rate of 5.65 g VS/L. The average methane production yield was about 420 L/kg added VS.

Alvarez *et al.* (1992) reported that biomethanation of food-market waste resulted in a production of 0.64 m^3 biogas/kg TSs added. The biogas yield from canteen wastes, which was a mixture of FVW, when subjected to anaerobic digestion varied from 0.82 to 0.9 m^3/kg of VS added (Nand *et al.*, 1991). Viswanath *et al.* (1992) reported a production of 0.12 m^3 biogas/kg TS added with HRT of 16 days and the biogas yield varied between 0.6 and 1.0 m^3/kg VS/day from the same type of waste. Biomethanation of banana peel and pineapple wastes studied by Bardiya *et al.* (1996) at various HRTs showed a higher rate of gas production at lower retention time.

The biochemical methane potential of 54 fruits and vegetable wastes samples and eight standard biomass samples were determined by Gunaseelan (2004) to compare the extents and the rates of their conversion to methane. The ultimate methane yields (B_0) and methane production rate constant of fruit wastes ranged from 0.18 to 0.732 L/g VS added and 0.016 to 0.122 1/d, respectively, and that of vegetable wastes ranged from 0.19 to 0.4 L/g (VS) added and methane production rate ranged from 0.053 to 0.125 1/d, respectively. Temperature had no effect on the B_0 of mango peels; however, the conversion kinetics was higher at 35 °C than at 28 °C. All the samples of fruits and vegetable wastes tested gave monophasic curves of methane production. Substantial differences were observed in the methane yields and kinetics among the varieties in mango, banana, and orange. Different fruit parts within the same variety showed different yields in orange, pomegranate, grape vine, and sapota. The methane yields from the mango peels of some of the varieties, orange wastes, pomegranate rotten seeds, and lemon pressings were significantly ($P < 0.05$) higher than the cellulose. Methane yields and kinetics of vegetable wastes in different varieties as well as within different plant parts of the same variety differed. Onion peels exhibited yields significantly ($P < 0.05$) similar to cellulose, while a majority of the vegetable wastes exhibited yields greater than 0.3 L/g VS. Rotten tomato, onion peels, pest infested brinjal, lady's finger stalk, coriander plant wastes, cabbage leaves, and cauliflower stalk, turnip leaves, radish shoots, and green pea pods exhibited methane yields greater than 0.3 L/g VS added. Methane yields from these wastes varied among various varieties and different plant parts of the same variety. In coriander plant wastes, methane yield for leaves was higher than that of structural roots. These results provide a database on the extent and the rates of conversion of fruits and vegetable solid wastes that significantly contribute to the OF-MSWs.

Anaerobic digestion of wastewater from jam industries was studied in a continuous reactor with different OLRs and the optimum OLR was 6.5 kgCOD/m^3/day when it was operated with 3 days HRT. The biodegradability of wastewater in batch experiments was about 90%. The removal effciency of total COD and soluble COD were found to 82% and 85%, respectively. The specific methane production was 0.28 m^3/kg of COD removed/day (Mohan and Sunny, 2008).

Arvanitoyannis and Varzakas (2008) summarized in their recent review the main advantages of the biodegradation waste management as follows:

- It allows reducing the volume of organic wastes
- The biological hazard of the wastes can be controlled
- This system may be compatible with the other biological ELSS (greenhouses)
- The biogas manufactured can be used to produce electricity
- The water obtained in the biodegradation processes may be used for the other needs of the space vehicle

- A valuable effluent is also obtained, which eventually can be used as an excellent soil conditioner after minor treatments (Converti *et al.*, 1999)
- High OLRs and low sludge production are among the many advantages anaerobic process exhibit over other biological unit operations (Batstone *et al.*, 2001)

Biomethanization of fruit wastes is the best-suited treatment as the process not only adds energy in the form of methane, but also results in a highly stabilized and treated effuent. Compared to the aerobic method, the use of anaerobic digesters in processing these waste streams provides greater economic and environmental benefits and advantages. Besides reducing the amount of green house gases by controlled use of methane from waste, the substitution of oil and coal with bioenergy will result in saving the global environment by reducing the use of fossil fuels. Anaerobic digestion has many environmental benefits including the production of a renewable energy carrier, the possibility of nutrient recycling, and the reduction of waste volumes. Many kinds of organic waste have been digested anaerobically in a successful way, such as sewage sludge, industrial waste, slaughterhouse waste, FVW, manure, and agricultural biomass. The wastes have been treated both separately and in co-digestion processes. In co-digestion, it is important to consider the effects of the different incoming waste streams. Better handling and digestibility can be achieved by mixing solid waste with diluted waste. Furthermore, the successful mixing of different wastes results in a better digestion performance by improving the content of the nutrients and even reduces the negative effect of toxic compounds on the digestion process.

Many studies have been carried out both in batch and continuous modes, to determine how co-digestion of different organic solid wastes including FVW with cattle slurry can improve the efficiency of degradation (Callaghan *et al.*, 1999, 2002). The digestion of cattle slurries and of a range of agricultural wastes has been evaluated and has been successful according to Callaghan *et al.* (2002). Previous batch studies have shown that based on VSs reduction, total methane production and methane yield, co-digestions of cattle slurry (CS) with FVWs and with chicken manure (CM) were among the more promising combinations. A continuously stirred tank reactor (18 L) was used as a mesophilic (35 °C) anaerobic reactor to examine the effect of adding the FVW and CM to a system which was digesting CS (Callaghan *et al.*, 2002). The retention time was kept at 21 days and the loading rate maintained in the range 3.19–5.01 kg VS/m.d. Increasing the proportion of FVW from 20% to 50% improved the methane yield from 0.23 to 0.45 m^3CH_4 /kg VS added, and caused the VS reduction to decrease slightly. Chicken manure was not as successful as a co-digestate. As the amount of CM in the feed and the organic loading was increased, the VS reduction deteriorated and the methane yield decreased. This appeared to be caused by ammonia inhibition.

Gomez *et al.* (2006) compared the digestion of primary sludge (PS) against co-digestion of this waste together with the fruit and vegetable fraction of municipal solid wastes (FVF MSW), evaluating the production of gas, the influence of mixing conditions, and the performance of the system under different OLRs. The anaerobic digestion process was evaluated under static conditions and with different mixing conditions, with good results being found for the digesters with limited mixing, this representing an energy saving. The results for co-digestion of mixtures of PS+FVF MSW are better than those obtained from the digestion of PS on its own. Biogas production for co-digestion is much greater thanks to the larger VS content of this feedstock. Nevertheless, biogas yield and specific gas production for the two digestion processes are similar, with values in the range 0.6–0.8 L/g VS destroyed for the first parameter and in the range 0.4–0.6 L/g VS fed for the second. The co-digestion process was also evaluated at different OLRs under low mixing conditions, with stable performance being obtained even when the systems were overloaded. Co-digestion is of considerable technical interest, since it allows the use of existing installations and greatly increases biogas production and the energy produced in cogeneration units.

Anaerobic digestion can be carried out using three different systems, first batch systems with the advantage of simple design and process control, robustness toward coarse and heavy contaminants, and lower investment costs. The application of sequencing batch reactor (SBR) technology in anaerobic treatment of FVW is another batch system of interest due to its inherent operational flexibility, characterized by a high degree of process flexibility in terms of cycle time and sequence, no requirement for separate clarifiers, and retention of a higher concentration of slow-growing anaerobic bacteria within the reactor (Dague *et al.,* 1992) (Fig. 3.5).

Hydrogen–methane two-stage fermentation technology was developed by Nishio and Nakashimada (2007), in which the hydrogen produced in the first stage was used for a fuel cell system to generate electricity, and the methane produced in the second stage was used to generate heat energy to heat the two reactors and satisfy heat requirements. The technology proposed is effective for the treatment of sugar-rich wastewaters, bread wastes, soybean paste, and brewery wastes.

Evaluation of co-digestion with the OF-MSWs has been evaluated by Fernandez *et al*. (2005) for the treatment of fats of different origin. The process of co-digestion was conducted in a pilot plant working in the semicontinuous regime in the mesophilic range (37 °C) and the HRT was 17 days. During the start-up period the digester was fed with increasing quantities of a simulated OF-MSW (diluted dry pet food). When the designed organic loading was reached, a co-digestion process was

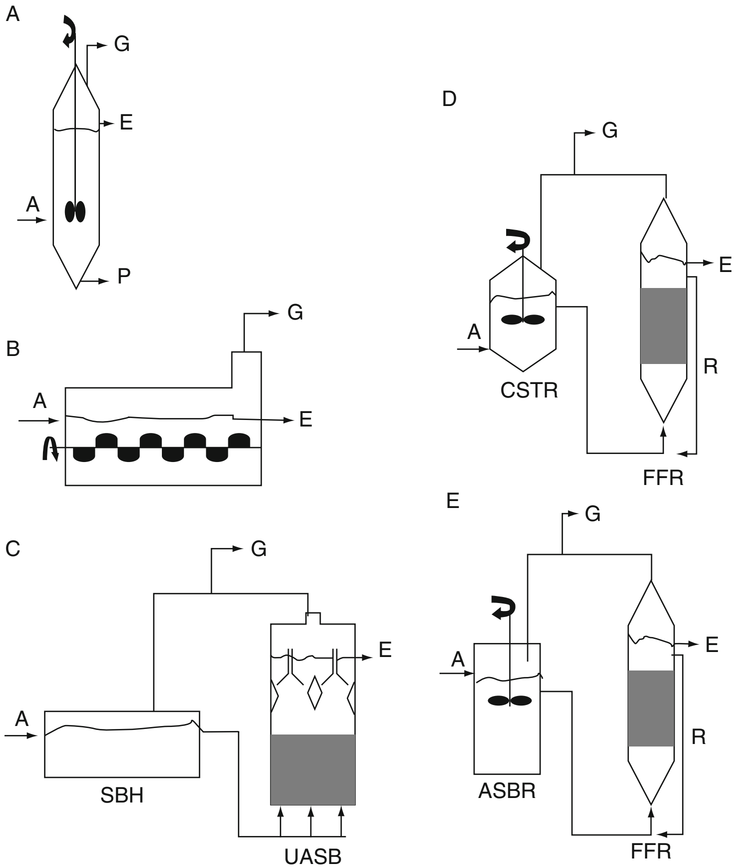

FIGURE 3.5 Processes used for FVW anaerobic treatment: (A) continuously stirred tank reactor (CSTR); (B) tubular reactor; (C) two-phase integrated anaerobic solid bed hydrolyser (SBH) and upflow anaerobic sludge blanket (UASB); (D) two-phase integrated anaerobic CSTR and fixed film reactor (FFR); and (E) two-phase integrated anaerobic sequencing batch reactor and FFR (Bouallagui *et al.*, 2005).

initiated. The fat used consisted of animal fat waste from the food industry, with a similar long-chain fatty acid (LCFA) profile to that of the diluted dry pet food. Animal fat was suddenly substituted by vegetable fat (coconut oil) maintaining the organic loading. The LCFA profile for vegetable fat is completely different from that of animal fat and simulated OF-MSW being short-chain-saturated LFCA the most predominant (lauric acid, mystiric acid, and palmitic acid accounting for the 74% of the total LCFA content). No accumulation of LCFA or VFAs was detected in either case. After a short adaptation period, total fat removal throughout the experiment was over 88%, whereas biogas and methane yields were very similar to those of simulated OF-MSW. This proved to be an effective method and suitable technology for the treatment of waste through anaerobic co-digestion of OF-MSW and fat wastes to obtain a renewable source of energy from biogas. Briefly, anaerobic digestion leads to the overall gasification of organic wastewaters and wastes, producing methane and carbon dioxide; this gasification contributes to reduction of organic matter and recovery of energy from organic carbon in cost-effective manner.

B. Biodiesel production

Biodiesel, as an alternative fuel, has many merits. It is derived from a renewable, domestic resource, thereby relieving reliance on petroleum fuel imports. It is biodegradable and nontoxic. Compared to petroleum-based diesel, biodiesel has a more favorable combustion emission profile, such as low emissions of carbon monoxide, particulate matter, and unburned hydrocarbons. Carbon dioxide produced by combustion of biodiesel can be recycled by photosynthesis, thereby minimizing the impact of biodiesel combustion on the greenhouse effect (Agarwal and Das, 2001).

Four different continuous process flow sheets for biodiesel production from virgin vegetable oil or waste cooking oil under alkaline or acidic conditions on a commercial scale were developed by Zhang *et al.* (2003). Two of them were alkali-catalyzed processes, the former using virgin oil and the latter using waste cooking oil. The remaining two processes were acid-catalyzed processes using waste cooking oil as the raw material. Detailed operating conditions and equipment designs for each process were obtained. Stainless steel was used for the trans-esterification reactor in the designs for the alkali-catalyzed processes in this study. The material of construction of other equipment in the alkali-catalyzed processes was carbon steel. For the acid-catalyzed system, a stainless steel (type 316) reactor was used. A technological assessment of these four processes was carried out to evaluate their technical benefits and limitations. Analysis showed that the alkali-catalyzed process using virgin vegetable oil as the raw material required the fewest and smallest process equipment units but at a higher raw material cost than the other processes. The use of waste cooking oil to produce biodiesel reduced the raw material cost. The acid-catalyzed process using waste cooking oil proved to be technically feasible with less complexity than the alkali-catalyzed process using waste cooking oil, thereby making it a competitive alternative to commercial biodiesel production by the alkali-catalyzed process. The alkali-catalyzed process using virgin oil was the simplest with the least amount of process equipment but had a higher raw material cost than other processes. The method using waste cooking oil was the most complex process with the greatest number of equipment pieces due to the addition of a pretreatment unit for free fatty acids removal despite the reduced raw material cost. The acid-catalyzed process using waste cooking oil had less equipment pieces than the previous process, but the large methanol requirement resulted in more and larger trans-esterification reactors, as well as a larger methanol distillation column. Methanol distillation was carried out immediately following trans-esterification to reduce the load in downstream units in this process but more pieces of equipment made from stainless steel material were necessary than the first two processes. In brief, for process simplicity, the alkali-catalyzed process using virgin vegetable oil is recommended. However, if the raw material cost is of concern, the acid-catalyzed process using waste cooking oil is a relatively simple process and proved to be a competitive alternative to the first two processes (Zhang *et al*., 2003).

Tashtoush *et al*. (2003) investigated the feasibility of utilizing a renewable and low-cost fuel raw material (a waste vegetable oil) as a diesel fuel replacement in small-scale applications such as in residential heating boilers. They examined the aspects of combustion performance and emissions of the ethyl ester of used palm oil (biodiesel) relative to the baseline diesel fuel in a water-cooled furnace. The combustion efficiency, η_c, and exhaust temperature, T_{exh}, as well as the common pollutants and emissions were tested over a wide range of air/fuel ratio ranging from very lean to very rich (10:1–20:1). All tests were conducted at two different energy inputs for both fuels. The findings showed that, at the lower energy rate used, biodiesel burned more efficiently with higher combustion efficiency and exhaust temperature of, respectively, 66% and 600 °C compared to 56% and 560 °C for the diesel fuel. At the higher energy input, the biodiesel combustion performance deteriorated and was inferior to diesel fuel due to its high viscosity, density and low volatility. As for emissions, biodiesel emitted fewer pollutants at both energy levels over the whole range of A/F ratio considered. World food consumption produces large quantities of waste (used or fryer) vegetable oil, WVO. In many world regions, most WVO produced is disposed of inappropriately. Consequently, the above-mentioned study was initiated to examine the potential of WVO as an alternative source of thermal energy.

C. Anaerobic treatment of dairy wastes

Anaerobic treatment applications for dairy industry wastewaters have been evaluated in a number of previous studies (Backman *et al*., 1985; Barford *et al*., 1986; Clanton *et al*., 1985; Hills and Kayhanian, 1985; Lo and Liao, 1986a,b; Lo *et al*., 1987; Mendez *et al*., 1989; Samson *et al*., 1985; Toldra *et al*., 1987). More recent information about anaerobic treatment practices of dairy waste streams is also presented by Demirel *et al*. (2005) (Tables 3.8 and 3.9).

TABLE 3.8 Typical operating conditions for anaerobic digesters (Wheatley, 1990)

Anaerobic digester configuration	Load (kg COD/ m^3day)	Retention	COD removal (%)
CSTR	0.5–2.5	1–5 days	80–90
Anaerobic filter	2–10	10–50 h	70–80
UASB	2–15	8–50 h	70–90
Fluidized bed	2–50	0.5–24 h	70–80

Conventional anaerobic treatment processes are often used for treating dairy wastewaters. Particularly anaerobic filters and UASB reactors are the most common reactor configurations employed. Actually, the UASB reactors are very suitable for treating food industry wastewaters, since they can treat large volumes of wastewaters in a relatively short period of time. More research should be directed toward treatment of dairy wastewaters in pilot and full-scale UASB reactors in near future, to make use of these potential advantages outlined. Lipid degradation and inhibition in single-phase anaerobic systems is frequently discussed in literature, since lipids are potential inhibitors in anaerobic systems, which can often be encountered by environmental engineers and wastewater treatment plant operators. Moreover, high concentrations of suspended solids in dairy waste streams can also affect the performance of conventional anaerobic treatment processes adversely, particularly the most commonly used upflow anaerobic filters. Thus, two-phase anaerobic digestion processes should be considered more often to overcome these problems that may be experienced in conventional single-phase design applications, since two-phase anaerobic treatment systems are reported to produce better results with various industrial wastewaters, such as olive oil mill and food-processing effluents, which are high in suspended solids and lipids content. When two-phase anaerobic digestion processes are evaluated as a whole, it is clear that the acid phase digestion of dairy wastewaters is actually investigated in various aspects. However, data especially for full-scale two-phase applications for dairy effluents in literature are scarce. Furthermore, in addition to degradation of lipids, protein solubilization should be investigated more comprehensively during acid phase digestion of dairy wastes with relatively high protein content, because there is contradictory information in literature about protein solubilization with different wastewater types during anaerobic acidogenesis. Since high rate anaerobic treatment of dairy wastes (or any industrial wastewater) with a relatively higher content of particulates, fats and proteins can often be problematic, modeling studies simulating biodegradation mechanisms of these components can extensively be explored. Removal of nitrogen and

TABLE 3.9 Anaerobic/aerobic treatment performance levels for dairy wastewaters (Demirel *et al.*, 2005)

Effluent type	System configuration	Removal	Application status	References
Milk bottling plant	DAF+upflow anaerobic filter (UAF)	38–50% BOD5 (DAF) >90% BOD5 (UAF) >85% COD (UAF)	Pilot scale	Kasapgil *et al.* (1994)
Cheese whey	Downflow–upflow hybrid anaerobic reactor (DUHR) + SBR	98% COD (DUHR) >90% COD (SBR)	Laboratory scale	Malaspina *et al.* (1995)
Cheese wastewater	UASB pond + aerated pond	98% (BOD5) 96% (COD) 98% (TSS)	Full scale	Monroy *et al.* (1995)
Synthetic milk powder/ butter factory wastewater	AAO activated sludge	>90% (COD)	Laboratory scale	Comeau *et al.* (1996)
Wastewater from an industrial milk analysis laboratory	Anaerobic filter + SBR	98% (COD), 99% (nitrogen)	Industrial Laboratory scale	Garrido *et al.* (2001)

phosphorus from dairy wastewaters has recently gained significant attention, due to more strict environmental regulations, so current research efforts clearly seem to focus on this particular topic. Recently, bench–pilot and full-scale applications of combined treatment methods for nutrient removal from dairy waste effluents are frequently encountered. It is obvious that as the regulations for discharge of nutrients become stricter in time, new modifications in existing treatment plants will eventually be incorporated. Finally, since the anaerobic digestion process is an imperative tool for the production of clean energy sources, such as hydrogen and methane, biogas production from high-strength dairy industry wastes will always be of paramount importance, as a valuable renewable energy source, for both developed and developing countries in future. Particularly, production of hydrogen by acidogenesis of high-strength dairy waste effluents is currently worth investigating.

D. Aerobic treatment of dairy wastes

Land disposal of whey as a waste product has been practiced not only in Europe but also in both the United States of America and Canada over the past 50 years. Although whey production has increased over the past 28 years by 165% in both countries, the utilization and disposal practices have remained essentially the same. However, because of its high BOD (40,000–60,000 mg/L), whey disrupts the biological process of conventional sewage treatment plants and its disposal into these plants has, therefore, been banned by many municipalities (Singh and Ghaly, 2006). Biodegradability evaluation of dairy effluents was studies by Janczukowicz *et al.* (2008). The results obtained proved that all dairy production effluents can be treated together, with the exception of whey, whose complex biodegradation demands may cause too much burden to any wastewater treatment technological system and thus should be managed within a separate installation. The pollutants in the cheese and cottage cheese whey proved to be the most resistant to biodegradation. Various methods for dairy waste treatment based on mesophilic aerobic and anaerobic digestions of whey and whey derivatives by yeasts have been reported by Cristiani-Urbina *et al.* (2000).

1. Thermophilic bioremediation for dairy waste management

A dairy farm processing 100 ton of milk per day produces approximately the same quantity of organic products in its effluent as would a town with 55,000 residents. However, legislative regulations for the dumping of whey are forcing industries to come up with alternatives to make this process of elimination environmentally safer. One with attractive potential involves the use of thermophilic microorganisms to produce a pasteurized, easily dewatered sludge at temperatures that facilitate enhanced levels of energy recovery. Processing options include the associated production of low COD treated wastewater (Kosseva *et al.*, 2001), or of added-value products such as xanthan gum (Papagianni *et al.*, 2001) and polyhydroxyalkanoates (Pantazaki *et al.*, 2003).

Aerobic treatment involving populations of thermophilic bacteria offers a wide spectrum of benefits. One of these is the potential for the biodegradation of organics in high-temperature wastewaters, which eliminates the need for cooling them *prior* to treatment. Operation under thermophilic conditions gives a high rate of biodegradation, which is 3–10 times higher than with a mesophilic process, and lends itself to high process stability. High temperatures also support the inactivation of the pathogens present in the wastewater (Cheunbarn and Pagilla, 2000; Nakano and Matsamura, 2001), which is one of the main aims of the treatment process. That makes aerobic thermophilic processing suitable for stabilization of the sludge and for rendering it hygienic, so that it can be exploited as a fertilizer.

As part of a project funded under the Fifth FRAMEWORK program of the European Commission, we have developed a bioremediation technology for cheese whey, associated with reduction of COD of the treated waste at elevated temperatures. This novel approach is an application of the standards for food industry environmental management systems, notably ISO 14000 (Boudouropoulos and Arvanitoyannis, 2000).

Main advantages of thermophilic biological methods are:

- Low mass yield
- Rapid kinetics
- High-temperature operation
- Stable process control of aerobic systems
- Production of pathogen-free products
- Energy generation

It is known that the composition of whey varies with a season, the acidity of nonpasteurized whey is higher during summer and the lactose concentration is lower than in winter. Kosseva *et al.* (2003, 2007) developed two strategies (two-stage and one-stage processes) for the bioremediation of blue Stilton whey applicable during whole year. It employed both naturally occurring thermotolerant organisms found in whey (LAB and yeast) and a thermophilic isolate. In 2003, a comparative study of two double-staged strategies was reported, using a thermophilic mixed population of *Bacillus* sp., isolated from a FVW. The source of these organisms shows robust properties and potential for degrading a broad spectrum of food wastes, for example, potato and grain distillery slops, and potato processing waters.

- *Strategy 1*: An anaerobic, mesophilic first stage, followed by an aerobic, mesophilic second stage (45 °C)

- *Strategy 2*: An anaerobic, mesophilic first stage (45 °C), followed by an aerobic, thermophilic second stage (55–65 °C)
- *Strategy* 3: An aerobic thermophilic single stage (55–65 °C) was reported in 2007.

In the first stage of the first two strategies, anaerobic mesophilic conditions allow the development of activity of *Streptococcus* sp. and ''lactic yeast'' (isolated from blue Stilton whey), which consume lactose and produce lactate, ethanol and carbon dioxide, and further biomass. In the second stage, aerobic conditions are employed which are favorable to the activity of an added mixed population of *Bacillus* sp., which degrades all available organic acids and ethanol, producing CO_2 and further biomass.

The following reaction scheme was proposed for the anaerobic mesophilic stage:

The homofermentative LAB (identified by Ercolini *et al.*, 2003) produce lactase, which hydrolyzes the lactose found in whey to glucose and galactose:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \quad (1)$$

Lactic acid is produced *via* the Emden–Meyerhof–Parnas glycolitic pathway, *via* pyruvic acid (*showing only the main reagents and products*):

$$2\,C_6H_{12}O_6 \rightarrow 4\,C_3H_4O_3 + 8\,H^+ \rightarrow 4\,C_3H_6O_3 + 4\,\mathrm{ATP} \quad (2)$$

The thermotolerant yeast directly utilizes lactose to produce ethanol and carbon dioxide:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4C_2H_5OH + 4CO_2 \quad (3)$$

Anaerobic biomass formation might be described by the following simplified reaction scheme:

$$a\mathrm{CH}_x\mathrm{O}_y + b\mathrm{H}_l\mathrm{O}_m\mathrm{N}_n \rightarrow \mathrm{CH}_\alpha\mathrm{O}_\beta\mathrm{N}_\chi + c\mathrm{H_2O} + d\mathrm{CO_2} \quad (4)$$

where CH_xO_y is a carbon source, $H_lO_mN_n$ is a nitrogen source, and $CH_\alpha O_\beta N_\chi$ is biomass formed.

During the thermophilic stage, the following reaction scheme, involving the *Bacillus* sp., was observed in chronological order for all temperatures:

Ethanol bio-oxidation to acetic acid:

$$C_2H_5OH + O_2 \rightarrow C_2H_4O_2 + H_2O \quad (5)$$

Bio-oxidation of acetic acid:

$$C_2H_4O_2 + 2O_2 \rightarrow 2CO_2 + 2H_2O \quad (6)$$

Bio-oxidation of lactic acid:

$$C_3H_6O_3 + 3O_2 \rightarrow 3CO_2 + 3H_2O \quad (7)$$

Bio-oxidation of citric acid:

$$C_6H_8O_7 + 4.5O_2 \rightarrow 6CO_2 + 4H_2O \quad (8)$$

Aerobic biomass formation:

$$eCH_xO_y + fO_2 + gH_lO_mN_n \rightarrow CH_\delta O_\varepsilon N_\varphi + hH_2O + iCO_2 \quad (9)$$

where $CH_\delta O_\varepsilon N_\varphi$ is biomass formed.

We propose the following bioremediation pattern for the aerobic single-stage process *(Strategy 3)* (Kosseva *et al.*, 2007):

LAB, *Lactococcus* sp. available in the Stilton whey, consume lactose, producing lactate:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4C_3H_6O_3 \quad (10)$$

Thermotolerant yeasts shift their metabolism to acetic acid and biomass production under aerobic conditions:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 6C_2H_4O_2 \quad (11)$$

Thermophilic bacteria *Bacillus* sp. consume lactate and acetate with main products carbon dioxide and biomass.

$$C_3H_6O_3 + 3O_2 \rightarrow 3CO_2 + 3H_2O \quad (12)$$

$$C_2H_4O_2 + 2O_2 \rightarrow 2CO_2 + 2H_2O \quad (13)$$

Biomass formation occurs simultaneously:

$$eCH_xO_y + fO_2 + gH_lO_mN_n \rightarrow CH_\delta O_\varepsilon N_\varphi + hH_2O + iCO_2 \quad (14)$$

A comparison of the effectiveness between the three strategies:

A comparison of the three bioremediation strategies for the management of dairy waste is summarized below:

Strategy 1 (two-stage)	Strategy 2 (two-stage)	Strategy 3 (one-stage)
Second stage 45 °C	Second stage 55–65 °C	55, 60, 65 °C
DOT $> 65\%$	DOT $< 80\%$	DOT $= 20, 40, 60, 80\%$
RQ $= 1$	RQ $= 1$	RQ $= 1$

Average velocity of lactate biodegradation: $V_{LA} \sim 0.50$ g/(L h)	$V_{LA} \sim 0.96$ g/(L h)	55 °C: $V_{LA} \sim 0.87$ g/(L h) $V_{COD} \sim 1.56$ g/(L h) COD removal $\sim$ 80–94%
Average velocity of COD removal: $V_{COD} \sim 0.74$ g/(L h)	$V_{COD} \sim 1.57$ g/(L h)	60 °C: $V_{LA} \sim 0.80$ g/(L h) $V_{COD} \sim 1.40$ g/(L h) COD removal $\sim$ 60–65.7%
Total removal of soluble COD = 68%	Total removal of soluble COD = 62.5%	65 °C: $V_{LA} \sim 1.01$ g/(L h) $V_{COD} \sim 1.35$ g/(L h) COD removal $\sim$ 60–77%
Total reduction of soluble protein = 59%	Total reduction of soluble protein = 47.5%	–

Following the mesophilic–thermophilic strategy, approximately 100% reduction of soluble COD and lactose was recorded accompanied with a 90% decrease in soluble protein in batch cultures. Applying single stage thermophilic strategy, high conversions in the range of 80–100% were obtained at 55 °C and DOT = 20, 40, 60, and 80%. Consumption of lactose and organic acids was ~90–100%. Biodegradation profiles at 60 °C and dissolved oxygen levels of 40% and 80% showed the conversions of lactose and organic acids in the range of 65–74%. At 65 °C thermophilic bacteria seem to grow mainly on lactate. Lactate consumption was between 87.5% and 92%. The efficiency of COD removal was approximately 20% lower than that observed at 55 °C. The demand for N-source in the course of the biodegradation process was higher under thermophilic than under mesophilic conditions, which also helped nitrogen removal from the whey effluent (Krzywonos *et al.*, 2008). Removal of nitrogen and phosphorus from dairy wastewaters has recently gained significant attention, due to more strict environmental regulations.

Summarizing, we developed the thermophilic bioremediation technology for treatment of cheese whey. The thermophilic microbial populations *Bacillus* sp. successfully reduced the polluting load of the whey stream. The process was capable of reducing pollution loads in cheese whey up to 93% at 55 °C, and up to 70% at 65 °C in a conventional aerated stirred tank bioreactor, in a way that complies with EU guidelines on sanitization of bio-waste. Mass balance based mathematical models have been developed using simplified modifications of the IAWQ Activated Sludge Model's concepts of ''lumping'' mixed populations and mixed substrates into a small number of ''clusters'' of ''equivalent'' substrate or biomass. Reasonably good fits to process data were obtained using these models over a range of temperatures, including those within the thermophilic region. Values of ''best fit'' model parameters were generated to predict biomass specific growth rates. The average specific growth rate calculated was 0.097 1/h at 55 °C while the experimental one was 0.079 1/h. At 65 °C the calculated average specific growth rate was 0.075 1/h while the experimental one was 0.089 1/h. The results obtained suggest that temperature may have exerted a larger influence on the biodegradation process than dissolved oxygen, as the composition of the microbial community changed with temperature over the range 55–65 °C. The average biomass yields generated varied from 0.350 (on lactose substrate) to 0.430 g/g (on lactic acid substrate) and were 0.86 g/g on acetic acid substrate, whereas yields calculated using the model varied from 0.325 (on lactose substrate) to 0.410 g/g (on lactic acid substrate), being 1.01 g/g on acetic acid substrate. Our investigations suggest that modeling of complex bioreaction systems *via* ''lumping'' of key substrates and microbial species into a limited number of ''equivalent clusters'' is worthy of consideration as a possible means of facilitating rapid process development and practical process operation.

Other members of our consortium (Cibis *et al.*, 2002) have investigated thermophilic aerobic biodegradation of potato slops (distillation residue) from a rural distillery. The COD levels of this fraction ranged from 49 to 104 g/L, and the main contributions to the COD come from organic acids, reducing substances and glycerol. The highest removal efficiency of approximately 77% was achieved at 60 °C using a similar mixed population of *Bacillus* sp., isolated from the same FVW and adapted to the above fraction.

IX. FCM ASPECTS AIMED IN SUSTAINABLE FOOD SYSTEM DEVELOPMENT

The current practices of pollution control and waste management cannot completely meet the increasingly strict requirements for the reduction of environmental contamination. A present day challenge for the manufacturer is to develop and master technical tools and approaches that will integrate environmental objectives into design decisions. The manufacturing industry has to include the optimization of product-integrated environmental protection into strategic planning, research and development.

These challenges cannot be met only by any individual enterprise but require a concentrated effort of specific actions and coordination of initiatives (Fitz and Schiefer, 2008). FCM aims at providing support for the identification and realization of ''best'' concepts for such actions and coordination needs. This support provides enterprises with the means for improving their own and the sector's competitiveness, sustainability, and responsibility toward the expectations of its customers and the society (Ondersteijn *et al.*, 2006).

A. User-oriented innovation in the food sector

According to CIAA (2007), one of the main issues the food sector needs to deal with is to *focus on changing consumer needs.* User-oriented innovation is not new to the sector (Grunert *et al.*, 2008). The *fork-to-farm* approach to food chains—meaning that all participants in the food chain should maximize value creation for the end user—has been promoted in various guises. But some recent developments make user-oriented innovativeness of the food chain more important, for example, public demands with respect to sustainable resource utilization, considerations concerning ethics and the environment and improvement of the work environment. The term *user-oriented innovation* has been defined as *a process toward the development of a new product or service in which an integrated analysis and understanding of the users' wants, needs, and preference formation play a key role* (Grunert *et al.*, 2008).

There are three main streams of the user-oriented innovative research in the food sector: (1) understanding user preferences, (2) innovation management, and (3) interactive innovation. Søndergaard and Harmsen (2007) have suggested a new product development model that takes an understanding of consumer quality perception as its point of departure. The basic message of the model is that the quality to be perceived by consumers is to be taken as a starting point, and that the concrete attributes to be built into the product, just as the concrete product attributes to be communicated to the prospective buyer, should be derived from this, and not the other way round. This approach is applicable to all three types of innovations, but is more straightforward in a type I innovation.

B. Market-oriented research

Several studies have concluded that market orientation is important for the successful outcome of innovation and this has also been documented specifically for the food industry (Kristensen *et al.*, 1998). Market orientation is often defined as a three-step process of collecting, disseminating, and responding to market information. Generating and disseminating information on user and market needs and incorporating these into product development is a prerequisite for user-oriented innovation, because it is essential to gain an understanding of user needs and then to incorporate this knowledge into product development.

C. Integrated product development and sustainability

New product development is an interdisciplinary activity requiring contributions from nearly all functions in a company or cross-functional cooperation and representation of user knowledge (Grunert *et al.,* 2008). Among the factors, that impact the success of new products, the use of cross-functional teams in product development is a key success factor (Cooper and Kleinschmidt, 1996).

Obtaining successful collaboration can be a challenge. This is usually attributed to differences in orientations, goals, departmental cultures as well as languages that functional representatives bring to the team. Especially, integration between marketing and R&D has been the focus of research indicating that disharmony between marketing and R&D is the rule rather than the exception (Moenaert and Souder, 1990). The interaction between development and use may vary along the ''life'' of a product. Synthesis oriented approaches for product development suggest a range of methods to be applied along a product's life cycle from conceptual idea and product design to manufacturing, distribution, sales and scrapping, recycling, and so on. As the food supply chain is complex, environmental impacts can occur in different places and different times for a single food product. LCA provides a way of addressing this problem. LCA gives businesses the opportunity to anticipate environmental issues and integrate the environmental dimension into products and processes. Important issues directly related to food processing are energy and waste management. Food production in general uses significant amounts of energy and produces relatively large amounts of wastes, particularly, packaging wastes (Mattsson and Sonesson, 2003).

D. The food market focus

The food sector faces three strategic developments regarding its production: (a) increasing demand for bioenergy, (b) limits in the availability of water, and (c) diminishing production resources (e.g., land for agricultural use). Furthermore, food production will be affected by pressure from a growing world population and the desire for an increased consumption of meat (Pingali, 2007). Possible changes in climate might magnify the consequences. Without innovations, consumers' need for affordable food without compromises in quality, and which continues to retain their trust, cannot be served in the long run. Consumers' perception of food quality is a dynamic variable. It might focus on products, processes, process management, or management issues such as fairness in trade, working conditions, environmental awareness, or the origin of products. Its understanding depends on lifestyles, cultures, and so on (Grunert and Wills, 2007; Lobb *et al.*, 2007). New types of efficient and responsive coordinated production, distribution, and communication networks must emerge that can support these changing demands, taking into account varying quality parameters, organizational conditions, and different requirements of market segments (Lindgreen, 2003; Taylor & Fearne, 2006). This may include, for example, new organizational structures for flexible chain-encompassing distribution and logistics systems that utilize advanced technologies for communication, control, or tracking and tracing, developments in quality preservation, new packaging and processing technologies, or organizational innovations such as parallel chains that could provide opportunities to better serve the needs of consumers.

Finally, consumers want to get the best quality at the lowest prices—but finding out what the best quality is may not always be a straightforward task. Even providing consumers with more information may not solve the problem, as the information may be ignored or misinterpreted. Public policy is often based on the assumption that more information is better, both to improve daily decision-making and in situations of crisis, but the research summarized by Grunert (2005) implies that more information may not only be without effect, but may in some cases increase confusion and consumer concerns. What is needed instead, is information of educational type, which adds value in both promotional but also knowledge-enhancing way.

Much food product differentiation has traditionally been dealt with at the processing level. However, there has also been a trend toward increasing differentiation already at the farm level. There are a number of reasons for this. Consumers demand some kinds of product differentiation that by their nature have to be dealt with at the farm level, such as increased animal welfare or organic production. Advances in biotechnology open up new possibilities for differentiation of both animal and plant production. Product differentiation at the processing level involves replication delays for competitors that are usually short, whereas differentiation that goes back to primary production gives better protection against competitive moves. The same conclusion may be valid to the waste product differentiation and reuse.

The outlined concept can be naturally transferred to several areas of industrial food production. The intentions of this research area are located at the development of techniques, which fulfill the conditions of environmental protection with costs to a minimum.

X. SUMMARY AND FUTURE PROSPECTS

1. Large quantities of food wastes are generated all over the world. The environmental pollution problems associated with conventional disposal methods have been an impulse for the search for alternative, environment-friendly methods of handling food wastes. These biodegradable wastes can be used as support-substrates in SSF to produce industrially relevant metabolites, such as enzymes, organic acids, flavor and aroma compounds, and polysaccharides, with a great economical advantage. Thus, cultivation of microorganisms on these wastes may be a value-added process capable of converting these materials into valuable products. However, much remains to be done in this area to develop commercial processes with techno-economical feasibility. It is envisaged that in the near future we should be able to develop industrial bioprocesses based on SSF for the production of industrially relevant products utilizing food wastes (Couto, 2008). Filamentous fungi are metabolically versatile organisms that are exploited commercially as cell factories for the production of enzymes and a wide variety of metabolites. It was possible to control simultaneous production of pectinolytic, cellulolytic, and xylanolytic enzymes by fungal strains of the genera *Aspergillus*, *Fusarium*, *Neurospora*, and *Penicillium* and generate multienzyme activities using a simple growth medium consisting of a solid by-product of the citrus processing industry (orange peels) and a mineral medium. Furthermore, the two-stage process proposed which includes coupling enzymatic treatment and solid-state fermentation, resulted in the production of fermentable sugars which could be converted to bioethanol (Mamma *et al.*, 2008). The ability to determine the flux of carbon, for example, into the desired product, and to identify and overcome bottlenecks in its production, will require a combination of bioreactor technology and global methods of analyses that are only now becoming possible.
2. The green production concept shows a good utilization potential for solid vegetable waste. It could achieve a reduction of investment and raw material costs and can contribute to a waste minimized food production. The development of bioadsorbents is a promising area to add value to vegetable residues. They will appear as a cheap and environmentally safe alternative to commercial ion-exchange resins (Laufenberg, 2003).
3. The exploitation of by-products of fruit and vegetable processing as a source of functional compounds and their application in food is a promising field which requires more interdisciplinary research in the following aspects:

- Food-processing technology should be optimized to minimize the amounts of waste arising
- Methods for complete utilization of by-products resulting from food processing on a large scale and at affordable levels should be developed. Active participation of the food and allied industries with respect to sustainable production and waste management is required
- Natural toxins such as solanin, patulin, ochratoxin, dioxins, and polycyclic aromatic hydrocarbons need to be excluded by efficient quality control systems including specific microanalytical methods for the characterization and quantification of organic compounds
- The bioactivity, bioavailability, and toxicology of phytochemicals need to be carefully assessed by *in vitro* and *in vivo* studies (Schieber *et al*., 2001)

   Functional foods represent an important, innovative, and rapidly growing part of the overall food market. However, their design, that is, their complex matrix and their composition of bioactive principles, requires careful assessment of potential risks, which might arise from isolated compounds recovered from by-products. Furthermore, investigations on stability and interactions of phytochemicals with other food ingredients during processing and storage need to be initiated. Since functional foods are on the boundary between foods and drugs, their regulation still proves difficult. In any case, consumer protection must have priority over economic interests, and health claims need to be substantiated by standardized, scientifically sound and reliable studies.

4. The ready availability of starch-based industrial wastes and their renewable nature merit their use as substrates for poly-betahydroxybutyrate (PHB) production from activated sludge. This would not only utilize the excess sludge generated and reduce the load on landfills, but would also contribute to reduction in the cost of PHB production by avoiding sterile conditions and pure carbon sources for maintenance and growth of pure cultures. PHB content is the most important factor affecting the production cost of PHB due to its effect on PHB yield and recovery efficiency, followed by cultural conditions and carbon substrates used (Khardenavis, 2007).
5. The comparative presentation of the various vegetable waste treatment methodologies showed that though bioremediation stands for the most environmentally friendly technique, its required longer treatment time in conjunction with its weakness to deal with elemental contaminants makes imperative the employment of a second alternative technique which could either be a membrane process (low energy cost, reliability, reduced capital cost) or a coagulation/flocculation method because of its low cost and high effectiveness. Biogas production appears to be another promising and energy effective waste treatment method (Arvanitoyannis and Varzakas, 2008).

6. Anaerobic digestion represents a commercially viable process to convert FVW to methane gas, a useful energy source. The overall results of anaerobic digestion of FVW suggest that the two-stage system is a promising process to treat these wastes with high efficiency in term of degradation yield and biogas productivity. This efficiency is possible by the adaptation of each ecosystem to its own substrate. The biochemical reactions involved in anaerobic digestion of FVW are taken subsequently under conditions similar to those of the rumen. It is appropriate to view the gastrointestinal tract as an ecological system and that by applying ecological principles, a better understanding of distribution and interaction of organisms can be achieved, and then it could help to design and construct a suitable bioreactor for FVW anaerobic treatment (Bouallagui *et al*., 2005).
7. Conventional anaerobic treatment processes are often used for treating dairy wastewaters (Demirel *et al*., 2005). Particularly anaerobic filters and UASB reactors are the most common reactor configurations employed. In fact, the UASB reactors are very suitable for treating food industry wastewaters, since they can treat large volumes of wastewaters in a relatively short period of time. More research should be directed toward treatment of dairy wastewaters in pilot and full-scale UASB reactors in near future, to make use of these potential advantages outlined. Lipid degradation and inhibition in single-phase anaerobic systems can often be encountered by environmental engineers and wastewater treatment plant operators. Moreover, high concentrations of suspended solids in dairy waste streams can also affect the performance of conventional anaerobic treatment processes adversely. Since the anaerobic digestion process is an imperative tool for the production of clean energy sources, such as hydrogen and methane, biogas production from high-strength dairy industry wastes will always be of paramount importance, as a valuable renewable energy source, for both developed and developing countries in future. Particularly, production of hydrogen by acidogenesis of high-strength dairy waste effluents is currently worth investigating.
8. The thermophilic bioremediation technology for treatment of high-strength organic wastewaters appears to combine the advantages of low biomass yields and rapid kinetics associated with high-temperature operation and stable process control of aerobic systems. It also has the potential of both producing pathogen-free products and the generation of energy out of the process. Furthermore, the average velocity of the thermophilic aerobic bioremediation was almost twice as high as that under mesophilic conditions and compared to the fact that COD and soluble protein levels were reduced during the thermophilic process compared to the mesophilic one, calls for further investigation of the opportunities of this particular promising technology

(Kosseva *et al.*, 2001, 2003, 2007). The aerobic technologies adapted by many dairy industries for processing of their wastewaters are usually, highly energy intensive and may lead to uncertainty regarding a stabilized performance, due to factors such as overloading and bulking sludge. On the contrary, anaerobic technologies are simpler, require a lower budget to operate, and have the potential of producing energy out of the utilization of the main process product, biogas with a high content in methane (Arvanitoyannis and Giakoundis, 2006).

9. Finally, the food industry uses the LCAs to identify the steps in the food chain that have the largest impact on the environment in order to target the improvement efforts. It is then used to choose among alternatives in the selection of raw materials, packaging material, and other inputs as well as waste management strategies. A new trend in society is when food is considered as the ethical and moral values, this will influence LCA. Combining LCA and social values, such as working environment and animal welfare, is the next step in development of food waste technologies.

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