PREFACE

Food wastes are organic residues from the processing of agricultural raw materials to food, which arise as liquid (wastewater) and solid wastes. The wastewater results from the cleaning processes or in the form of excessive or polluted process water. Its dry material content is typically less than 5% by mass. It possibly also contains organic or inorganic cleaning agents or disinfectants. Solid food wastes with an organic origin have remarkably high water content (mostly about 80% by mass). They are usually characterized by a constant quality and purity due to the forgone processes.

The fact that these substances are removed from the production process as undesirable ingredients makes them, by definition of most European legislations, wastes. The term ''by-product,'' which is common in industry, points up that these are mostly ulterior usable substances, often with a market value.

Waste disposal is one of the major problems facing most food processing plants. Agriculture as the traditional way of waste utilization—a consequential outcome because most raw materials are also from agricultural origin—is no longer available due to major changes in law and technology. Furthermore, new kinds of process engineering and resultant new products and markets make the utilization of waste increasingly interesting.

This book covers the main aspects of utilization of the food industry waste (defined thereby as by-product) and the treatments necessary to discard waste to environmental acceptors. It cannot cover the entire spectrum of utilization of solid and liquid wastes of the food industry. The multiplicity of possible utilizable ingredients and technologies alone would exceed such an undertaking. For this reason many utilization possibilities are briefly and exemplarily mentioned.

The first chapter shows the exigency for utilization of food wastes and gives an overview about ways of utilization. The next chapter introduces the main ideas on treatment of food waste according to the ISO 14001 standards and the EU directives concerning the environmental performance of the food industry. The following chapters cover processes for wastewater treatment in general and applications of treatment of specific wastewater from different branches. The technology of anaerobic fermentation, thereby used among others for biogas production, is described in Chapter 9 as a method for specific degradation of solid wastes. The energy generation with biogas production is economically interesting, but direct substantial utilization of food waste is also efficient. Different examples with direct practical applicability demonstrate this substantial utilization. The range of possible usable wastes is among fish, fruit, fats and spent grains (Chapters 10–13). They can be used for the production of food ingredients, e.g., polyphenols, protein isolates, and dietary fibers, but also for nonfood products like bricks or fuel. Despite the generally high water content incineration is technically feasible as exemplified by spent grains in Chapter 14. Finally, composting of agricultural and food waste is covered in Chapter 15.

Athens and Weihenstephan in February 2006
Vasso Oreopoulou
Winfried Russ

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Introduction to Food Waste Treatment: The 14001 Standards

Vassilis Gekas and Maria Nikolopoulou

2.1. INTRODUCTION

The aim of this chapter is to introduce the main ideas concerning treatment of food waste in the spirit of the standards and directives of the EU and to examine the environmental performance of the food industry as it seeks to comply with the ISO 14001 standards. How is the food scientist and/or engineer going to comply with these requirements? Basic tools in the hands of the food scientist and/or engineer is the knowledge of physical and physicochemical properties of the foods, the mass and energy balances, the application of these principles to the unit operations, and unit processes taken place in the industry or activity of concern. This enables the food scientist and/or engineer to predict the quantities and compositions of the various streams, especially those of the effluents. Then the environmental behavior of the organization could be obtained. From this point and on the remediation tactics and strategies could be followed. Life cycle analysis is important because not only the inputs and outputs of a given food industry or in general food activity is of importance for the environment but also the pre- and posthistory. Usually the input to an organization is the output of another organization and vice versa. Environmental aspects of a food endeavor is not a onetime concern. In the beginning, we ensure compliance with the environmental laws and regulations. Follow up is also a requirement set by the EU directives.

2.2. WHAT IS ISO 14001?

These standards are a part of the more general series of environmental standards ISO 14000. ISO 14001 is the most well-known standard of the series. It was first

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published in 1996, and is still the only standard of the 14000 series with respect to which it is currently possible to be certified by an external certification authority. This standard can be applied by any organization that wishes to implement, maintain, and improve an environmental management system, and also to:

- assure itself of its conformance with its own stated environmental policy (those policy commitments of course must be made),
- demonstrate conformance,
- ensure compliance with environmental laws and regulations,
- seek certification of its environmental management system by an external third party, and
- make a self-determination of conformance.

In 1996, the EC directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control also was issued. The aim is to map any organization's (not only food of course) environmental performance. It is therefore the aim of this chapter to introduce the food scientist and/or engineer to those regulations and to show a way to comply with them. The organization will order the ISO 14001 toolkit and also the above directive. The contents of the ISO 14001 are the following:

Part 1 - Introduction and Background

Chapter 1	Introduction to Integrated Management Systems
Chapter 2	ISO 14000 and Environmental Management Systems
Chapter 3	Third-Party Registration
Chapter 4	Introducing ISO 14001

Part 2 - Policy and Planning

Chapter 5	Environmental Policy
Chapter 6	Environmental Aspects
Chapter 7	Legal and Other Requirements
Chapter 8	Objectives and Targets
Chapter 9	Environmental Management Program

Part 3 - Implementation and Operation

Chapter 10	Structure and Responsibility
Chapter 11	Training, Awareness, and Competence
Chapter 12	Communication
Chapter 13	Environmental Management System Documentation
Chapter 14	Document Control
Chapter 15	Operational Control
Chapter 16	Emergency Preparedness and Response

Part 4 - Checking and Corrective Action

Chapter 17	Monitoring and Measurement
Chapter 18	Non-conformance and Corrective and Preventive Action

The directive mentioned above consists of 22 articles and 4 annexes. Examples of organizations and the pollutants to examine are also given (www.homestead.com, 2005).

The above is just an introductory step toward the actions, which have to be taken by the organization. This is not the objective of this chapter. The main aim is to prepare the future engineer manager to face the environmental issues of the organization for which he/she is going to work for.

2.3. THE FOOD SECTOR AS AN ORGANIZATION

2.3.1. Inputs

Figure 2.1 shows a typical food organization with its interactions with the environment. The whole agrofood sector could be thought of as an organization or only the food packaging unit or a certain food industry or even a part of an industry. The entire agrofood sector is considered as the organization (Gekas and Balta, 2005).

It consists of:

- primary production,
- postharvesting,
- production, and
- packaging.

In the input side we have:

- raw materials,
- water, and
- energy.

Water is considered separately because of its importance not only in the manufacturing but also for cleaning and hygiene. Attention has to be paid to the life cycle analysis of the inputs. In the raw materials it could be a possible

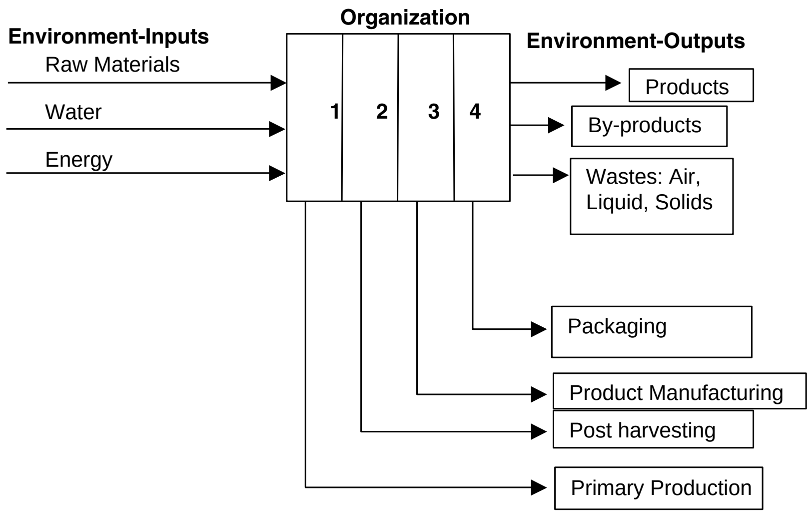

Figure 2.1. Structure of a food factory.

contamination by pesticides. Water also is important. Where is it taken from? What is its analysis? Is water quality conforming to the specifications in the various uses of the water inside the organization?

Where is the energy coming from? Is the energy coming from environmentally friendly sources? From renewable sources? From conventional sources? The latter question is a crucial one. If a food activity is planned for many decades to come, then it should be taken into consideration that the conventional resources, namely oil, natural gas, and hydrocarbons, are rather limited and are more or less environmentally unfriendly. Also, are the outputs of the organization recycled so that water and energy could be used as inputs?

These questions and trying to find the right answers will enable one to tackle the environmental problems in a creative way. An attractive solution is to use a part of the wastes (after having recovered valuable substances) as biomass to produce biofuels for the energy requirements of the unit or the organization. Also take into account that the conventional fuel deposits are going to be exhausted in a few decades. According to information sources from oil concerns and statistics from the energy authorities of United States and Canada the deposits of oil, natural gas, and hydrocarbons will last 26, 34, and 86 years, respectively, with the assumption that no new deposits are going to be found and that the demand increase per year will be at maximum 10%.

Foods are necessary for the survival of *Homo sapiens*. It has been found that foods are *sine qua non* for the maintenance of human health. Foodaceuticals is a modern concept and challenge.

Will nuclear energy be the future energy source? But this is environmentally the most unfriendly energy form, both short term and even more risky long term.

Will it be hydrogen? Yes, but from which source? If the answer is water splitting then again by which energy are we going to split the water molecule? Nuclear energy? The same problem arises again.

Sun and wind, the solar and eolian forms of energy are quite attractive but depend on the weather facilities at a place. Geothermal field is another example. In Crete, it is thought that such energy sources be applied in connection with food manufacturing. But biomass is international. This is a smart choice to make. Solve the negative consequences problem with a positive supply of energy solution. Incineration of municipal wastes after a proper predrying in Italy or Greece could be possible, for example, to produce energy, solving at once two serious problems. There are areas with shortages of both energy and water. There are technological solutions to solve the problem of both input demands by the food organization. Sea or brackish water desalination plants can be driven by sun or by the wind. This is really a compliance of the input side to the organization in an environmental protection spirit. The engineer will face three big questions:

- How to avoid the contamination of raw materials from pesticides and other pollutants?
- How to provide ''environmentally friendly'' produced water to the organization?
- How to provide ''environmentally friendly'' produced energy to the organization?

2.3.2 Outputs

As shown in Figure 2.1 there are three kinds of outputs from the food, and not only from the food organization.

- The products. Special care would be taken in order to avoid
  - raw material contamination, and
  - contamination from the production line itself. Therefore, hygienic design is needed.
- The by-products. The same is valid as for the products.
- The waste effluents
  - to the air,
  - to the surface waters, and
  - to the soil or the groundwater.
- The wastes could also be
  - gas emissions,
  - liquid phases, aqueous or of different solvents, and
  - solids.

A considerable part of the latter are the used packages after food consumption. In the Royal Kingdom according to a statistic in the year 1996, one third of all solid wastes are of the food packages origin (Gekas and Balta, 2001). What will be the strategy of the environmentally responsible scientist concerning those outputs, wastes effluents in particular?

The strategies are discussed in Section 2.7. In Sections 2.8 and 2.9, the focus is on the strategies of recovery and achieving in an environmentally friendly way the production of high-value products from wastes using the membrane bioreactor concept. Before that the hygienic and risk analysis is discussed in Section 2.6. Basic knowledge of physical properties and mass and energy balances are given in Sections 2.4 and 2.5, respectively.

2.4. PHYSICAL PROPERTIES

The following properties of the foods and food constituents are necessary for the prediction of the environmental performance:

1. Thermodynamic properties: partition coefficients, activities, and chemical potentials.

Through the knowledge of these properties we can predict the distribution of a given component between two or more phases, for example, hexane in the kernel oil.

2. Kinetic data K, K_m for enzyme catalyzed reactions.
3. Physical properties: viscosity, density, and diffusivity.
4. Biological oxygen demand (BOD) Chemical oxygen demand (COD) Suspended solids (SS)
5. Toxic and hazardous: A difference in the values of COD and BOD indicates probably a toxic or hazardous character of the effluents because in this case nonbiodegradability is occurring.

A good software, such as the Super Pro by the Intelligen, Inc., company includes a database of the above properties. Also the database produced as the outcome of the DOPPOF (the initials are ''database of physical properties of foods'') European project contains the physical properties of a great number of foodstuffs (www.nelfood.com). Other sources of physical property data are in Gekas (1992) and Rahman (1995).

2.5. MASS AND ENERGY BALANCES

A typical case is the combination of two unit procedures, a synthetic process, A, followed by a separation unit operation, B (Figure 2.2a). In the food industry process A is a chemical reaction, an enzyme catalyzed process, or in general biocatalyzed process.

A could be a:

- feed tank
- mixing tank
- a reactor or bioreactor

and B could be a separation module, such as a:

- decanter
- centrifuge
- membrane unit
- activated carbon fixed or fluidized bed

According to the case in the system of Figure 2.2a more pretreatment or posttreatment steps could be added. Those steps could be unit operations or unit

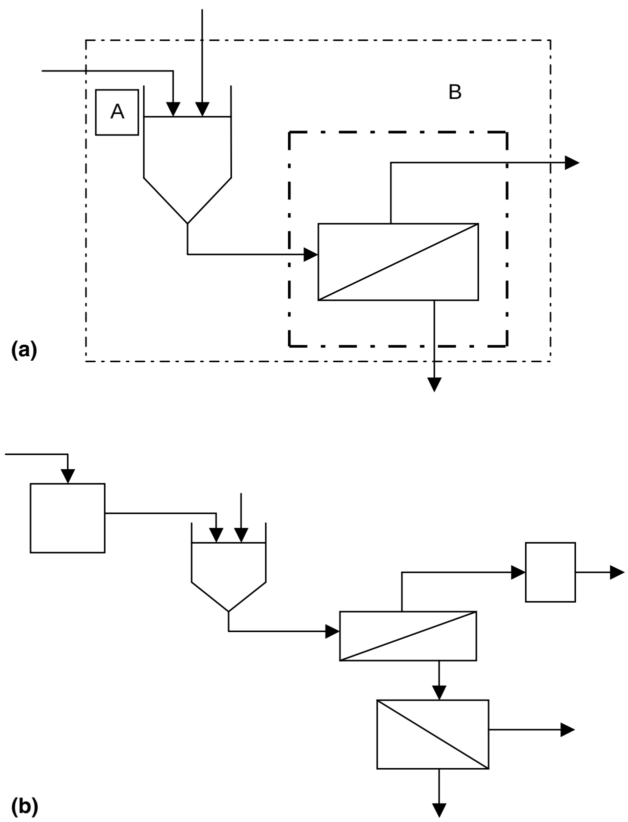

Figure 2.2. **(a).** A combination between a synthetic and a separation process. **(b)**. More pre- and posttreatment steps added.

processes or unit bio-processes. A conserved property such as mass (total or the mass of a given component) or energy fulfill the balance equations. A basic requirement for any balanced equation to apply is to define very carefully the so-called control volume. For example, in Figure 2.2b the control volume could be the unit A or B or both procedures A+B. In the former case we have a specific balance. A balance applied to the overall process is an overall or general balance. Concerning mass balances a total balance concerns the conservation of the total mass, whereas a certain component follows a partial mass balance.

2.5.1. Kinds of Balances

It is understood that there are four kinds of mass balances:

1. total and overall (general)
2. partial and overall (general)
3. total and specific
4. partial and specific

The balance of any conserved (extensive) property, F, can be written as:

(1) $$\sum F_{in} = \sum F_{out} - \int dF/dt$$

For large-scale times or when generally there are no source or accumulation terms:

(2) $$\sum F_{in} = \sum F_{out}$$

In the partial mass balances, sources usually appear. Then the inputs equal the outputs $\pm$ the sources.

2.5.2. Example of Balances

2.5.2.1. Evaporation of Tomato Paste

For 200,000 kg/day of tomato paste at 35°C, 5% dry solids (DS) to be converted to 30% DS in a one-stage evaporator (Figure 2.3) operating at 93°C (77 kPa, $H = 2664$ kJ/kg, $h = 387$ kJ/kg), where H and h are enthalpies of the water in the steam and liquid form, respectively. Saturated steam was fed to the heat exchanger 1250 kPa ($T = 190$°C, $H = 2786$ kJ/kg, $h = 808$ kJ/kg). The Cp of the tomato paste was 4.01 kJ/kg°C.

a) What is the quantity of steam removed?
   Solution: Considering 24 hours of operation and neglecting the solids removed by the steam, the partial balance of solids is:

$$F x_F = L x_L.$$

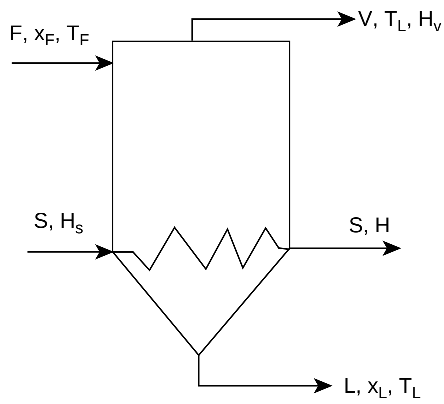

Figure 2.3. Single-stage evaporator.

Substituting $F = 200{,}000$ kg, $x_F = 0.05$, $x_L = 0.30$ gives $L = 33{,}333$ kg. The total mass balance is:

$$F = V + L,$$

therefore $V = 166{,}667$ kg.

b) What is the steam recovery?
Solution: 93°C is taken as the reference temperature. The total energy balance is

$$F\,c_{\mathrm{p,\,pulp}}\,(T_F - T_{ref}) + S\,(H_s - h_{\mathrm{ref}}) = Lc_L\,(T_L - T_{\mathrm{ref}}) + V(H_V - h_{\mathrm{ref}}) + S\,(h_s - h_{\mathrm{ref}})$$

Substituting $F = 200{,}000$ kg, $c_{\mathrm{p,\,pulp}} = 4.01$ kJ/kg°C, $T_F = 35$°C, $T_{\mathrm{ref}} = T_L = 93$°C, $H_s = 2{,}786$ kJ/kg, $h_{\mathrm{ref}} = 387$ kJ/kg, $V = 166{,}667$ kg, $H_{\mathrm{v}} = 2{,}664$ kJ/kg, $h_s = 808$ kJ/kg, and finally $S = 215{,}378$ kg. Recovery of steam:

$$V/S = 77.4\%.$$

c) Which is the contact heat area, if U the overall heat transfer coefficient is 3,100 W/m^{2}K?
Solution: If U the overall heat transfer coefficient is 3,100 W/m^{2}K

$$q = U\,A\,\Delta T = S(H_s - h_s).$$

Substituting $S = 2.5$ kg/s, $H_s = 2{,}786$ kJ/kg, $h_s = 808$ kJ/kg, $U = 3{,}100$ W/m^{2}K and $\Delta T = 190\text{-}93 = 97$ K, A is calculated to be 16.4 m^2.

2.5.2.2. Two-stage Evaporation

For the same operation as previously described but with a two-stage evaporation carrying out (Figure 2.4), the previously calculated heat transfer contact area

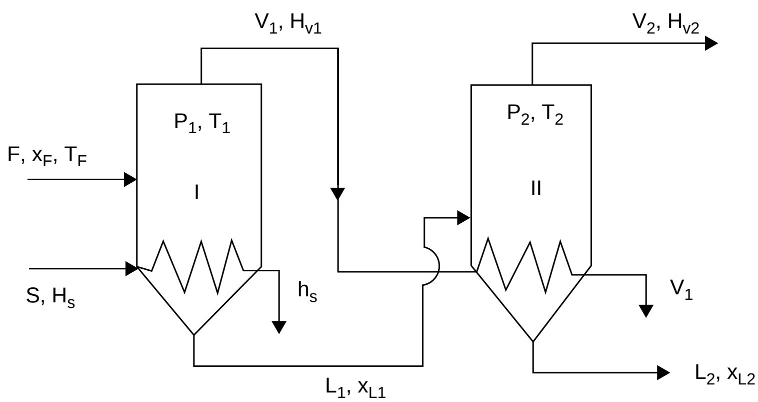

Figure 2.4. Two-stage evaporator.

16.4 m^2 was taken as the invariant. First evaporator is at 150°C (476 kPa, $H = 2{,}747$ kJ/kg, $h = 632$ kJ/kg), and the second at 93°C (77 kPa, $H = 2{,}664$ kJ/kg, $h = 387$ kJ/kg). $U_1 = 3{,}750$ W/m^{2}K and $U_2 = 3{,}300$ W/m^{2}K.

a) What is the heat balance of the second evaporator
Solution:

$$q_2 = U_2 A_2 \Delta T_2 = V_1 (H_{v1} - h_{v1}).$$

Substituting $H_{v1} = 2{,}747$ kJ/kg, $h_{v1} = 632$ kJ/kg, $U_2 = 3{,}300$ W/m^{2}K, $A_2 = 16.4$ m^2, $\Delta T = 150–93 = 57$ K, the quantity of steam removed from the first evaporator is $V_1 = 1.28$ kg/s $= 110{,}744$ kg/day.

b) What is the solid content (DS) of the concentrated effluent of the first evaporator?
Solution: Total mass balance specific in evaporator 1:

$$F = V_1 + L_1.$$

$F = 200{,}000$ kg/day and $V_1 = 110{,}744$ kg/day so that $L_1 = 89{,}256$ kg/day. Neglecting solids removed by the steam effluent V_1, the partial specific solids balance is:

$$F x_F = L_1 x_{L1}.$$

$F = 200{,}000$ kg, $L_1 = 89{,}256$ kg and $x_F = 0.05$ gives us the fraction $x_{L1} = 0.11$.

c) What is the steam quantity required in the first evaporator?
Solution: 150°C is taken as the reference temperature and the specific total energy balance is:

$$F\, c_{\mathrm{p,pulp}}\, (T_F - T_{\mathrm{ref}}) + S(H_s - h_{\mathrm{ref}}) = L_1\, c_{L1}\, (T_{L1} - T_{\mathrm{ref}}) + V_1(H_{v1} - h_{\mathrm{ref}}) + S(h_s - h_{\mathrm{ref}})$$

Substituting $F = 200{,}000$ kg, $c_{\mathrm{p,\,pulp}} = 4.01$ kJ/kg°C, $T_F = 35$°C, $T_{\mathrm{ref}} = T_L = 150$°C, $H_s = 2{,}786$ kJ/kg, $h_{\mathrm{ref}} = 632$ kJ/kg, $V_1 = 110{,}744$ kg, $H_V = 2{,}747$ kJ/kg, $h_s = 808$ kJ/kg we find $S = 106{,}786$ kg.

d) What is the new steam economy?
Solution: The total overall balance is:

$$F = V_1 + V_2 + L_2,$$

Substituting $F = 200{,}000$ kg, $V_1 = 110{,}744$ kg, και $L_2 = 33{,}333$ kg (from the previous problem), we find $V_2 = 55{,}923$ kg. Steam recovery $= (V_1 + V_2)/S = 1.56 = 156\%$. The economy (recovery) of the steam is very much improved with the new concept of the two-stage evaporation unit (Geankoplis, 2003).

2.6. INSIDE THE ORGANIZATION: HYGIENIC DESIGN, HACCP

A very important coordinate of the ultimate goal for food quality is the microbiological safety (prevention of the development of microorganisms) and the elimination of foreign objects that possibly could contaminate our products and by-products. The hygienic design of any production, as well as rules to avoid risks are required (HACCP: Hazard Analysis of Critical Control Point) (www.ehedg.org, 2005).

The hygienic design concerns the machines, tanks, pipes, pumps, valves, instrumentation, the locals (roofs, corners, walls, grounds, storage areas, etc.), and the personnel. Guidelines for the hygienic design have been edited by the European organization EHEDG—the European Hygienic Engineering and Design Group. The EHEDG provides guidance on the hygienic engineering aspects of manufacturing of safe and wholesome food. This is achieved through production, publication, and updating of guidelines available in several languages. To bridge the gap between theory and practice, training modules will be created based on the guidelines equipment approval through certification to assist equipment suppliers and food manufacturers. The EHEDG has EC support through the thematic network, HYFOMA, which is the European network for hygienic manufacturing of food. Its goal is guideline development and dissemination of information.

Concerning the HACCP there are seven principles:

- Analyze hazards: Potential hazards associated with a food and measures to control those hazards are identified. The hazard could be biological, such as a microbe; chemical, such as a toxin; or physical, such as ground glass or metal fragments.
- Identify critical control points: These are points in a food's production—from its raw state through processing and shipping to consumption by the

consumer—at which the potential hazard can be controlled or eliminated. Examples are cooking, cooling, packaging, and metal detection.

- Establish preventive measures with critical limits for each control point. For a cooked food, for example, this might include setting the minimum cooking temperature and time required to ensure the elimination of any harmful microbes.
- Establish procedures to monitor the critical control points. Such procedures might include determining how and by whom cooking time and temperature should be monitored.
- Establish corrective actions to be taken when monitoring shows that a critical limit has not been met, for example, reprocessing or disposing of food if the minimum cooking temperature is not met.
- Establish procedures to verify that the system is working properly, for example, testing time-and-temperature recording devices to verify that a cooking unit is working properly.
- Establish effective recordkeeping to document the HACCP system. This would include records of hazards and their control methods, the monitoring of safety requirements and action taken to correct potential problems. Each of these principles must be backed by sound scientific knowledge, for example, published microbiological studies on time and temperature factors for controlling foodborne pathogens.

2.7. WASTE TREATMENT STRATEGIES

In general there are three sorts of strategies:

1. The end of pipe abatement
2. The reduction at source
3. The zero-point discharge

If the first strategy is to be followed, the organization can just discharge the wastes to a nearby biological station, which will treat the industrial wastes along with the municipal ones or may have an installation of primary, secondary, and tertiary wastewater treatment. A thorough knowledge of the production process and its unit operations and processes is required in order to be able to apply the second strategy in the practice.

For example, you are the new responsible man (or woman) for the environmental management policy in your company, which is a potato fries production. One of the unit operations is blanching in hot water. Blanching in hot water has some adverse effects. You have followed the food engineer course so you know everything about blanching. You know that due to driving forces there will be a loss of, for example, Ca^{2+} in the hot water. This calcium quantity will pass into the waste of the industry. The previous policy of the company was to pay a fee to discharge this waste to the nearby aeration installation for the municipal wastes. The community asked for an increase of the fee because they found that your calcium causes troubles in the tertiary treatment of the aeration installation. What are you going to do? If you follow the end of pipe strategy, probably you think to remove Ca^{2+} before the discharge of the potato waste to the community's biological plant. Another alternative would be to intervene in the blanching operation. Change from hot water to steam, or even use a membrane operation already in that step and not end of pipe to avoid having large volumes at the end. These measures are reduction at source.

Finally, in the food industry zero-point discharge is desired, since it is assumed that there is no environmental contamination through the (raw materials and water) inputs, everything found in the wastes is in principle possible to retrieve and utilize. An example of zero discharge is provided by the dairy industry, which is the only food industry so far advanced in what is regarded as the environmental performance. Zero discharge means not only that a waste like whey, for example, is 100% utilizable by retrieving all valuable substances from it, but also that cleaning waters containing milk are treated to milk and pure water achieve which is recycled or otherwise allowed to be discharged.

2.8. THE KEYWORD: RECOVERY

The magic word expressing the particularity of food wastes is ''recovery.'' Food waste should not be considered as wastes but as raw materials to develop high additive value as new products.

Thus monosaccharides can be obtained through selective hydrolysis of lactose that has been recovered from whey. Oligopeptides can be obtained through peptic hydrolysis of whey protein concentrate (WPC) isolated from whey. Valuable phenol compounds could be recovered from olive oil mill wastes and then used as raw materials for the development of cosmetics and pharmaceuticals. Ethanol could be produced through the enzymatic conversion of cellulose-rich wastes. Pectin could be produced from fruit juice effluents; the list is long indeed.

An example of using appropriate technology is the production of WPC, which can be obtained from whey following the steps below:

- Membrane separation, reverse osmosis or ultrafiltration (RO and UF)
- Evaporation
- Drying

Protein content in the whey is 1.5%. The membrane concentration factor could be as high as 18. This means that the effluent leaving the membrane step could have a protein concentration of 27%. This could be brought up to a value of 54% through a two-stage evaporation unit and the final protein concentration could be 80% after the drier.

2.9. APPLICATION OF MEMBRANE REACTORS TO BY-PRODUCTS TREATMENT

Enzymes are usually involved in the conversions mentioned above. Beta galactosidase is the enzyme hydrolyzing lactose to glucose and galactose. The same enzyme under appropriate conditions of the reaction also has synthetic properties, i.e., galactose molecules get attached to a lactose molecule giving oligosaccharides. Peptidases convert the proteins to peptides. Alpha amylase converts the starch into less viscous intermediate hydrolysates, which upon further hydrolysis by glycol amylase yield glucose.

Beta amylase converts the starch to maltose. Maltose is hydrolyzed by alpha glycosidase to glucose. Those are a few examples. The device to carry out such a reaction with a subsequent separation is known as a membrane reactor or bioreactor. A frequent application is the CSTR bioreactor, which is a continuously stirred tank reactor with a membrane unit, usually ultrafiltration, downstream. This principle is shown in Figure 2.5. One of the advantages with this kind of reactor is when the substrate is macromolecular and the product micromolecular. Then as the product is removed in the permeate and the substrate with the enzyme recirculates in the retentate and to the reactor tank, possible product inhibition effects are avoided.

Another kind of reactor uses the immobilized enzyme form, the enzyme being immobilized on the surface of or entrapped inside the membrane matrix. Then the membrane unit is both the place for the reaction and the separation. Other concepts used are loading the biocatalyst enzymes or whole cell in the shell side of hollow fibers, passing the substrate through the hollow fiber's lumen. The module follows a passive mode of operation, with no pressure exerted. The substrate being permeable to the membrane diffuses from the lumen (the hole) of the fiber to the shell, it reacts there with the biocatalyst and the products diffuse back to the lumen and are taken away (Figure 2.6) (Gekas, 1986).

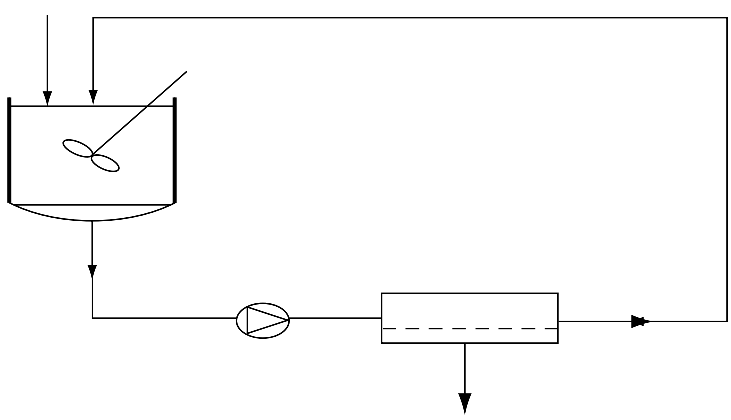

Figure 2.5. CSTR-UF reactor.

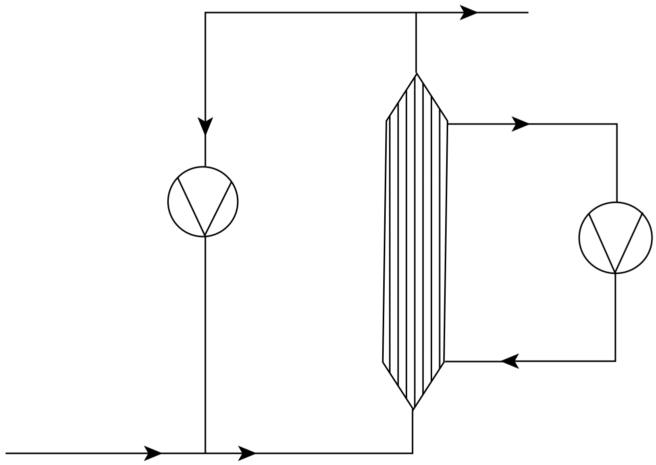

Figure 2.6. Hollow fiber reactor.

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