1

Introduction

1.1 Characteristics of agricultural and food wastewater

Whenever and wherever food in any form is handled, processed, packed and stored, there will always be unavoidable generation of wastewater. Wastewater is the most serious environmental problem in the manufacturing and processing of foods. Most of the volume of wastewater comes from cleaning operations at almost every stage of food processing and transportation operations. The quantity and general quality (i.e., pollutant strength, nature of constituents) of this generated processing wastewater have both economic and environmental consequences with respect to its treatability and disposal.

The cost for treating the wastewater depends on its specific characteristics. Two significant characteristics that dictate the cost for treatment are the daily volume of discharge and the relative strength of the wastewater. Other characteristics become important as system operations are affected and specific discharge limits are identified (e.g., suspended solids). The environmental consequences in inadequate removal of the pollutants from the waste stream can have serious ecological ramifications. For example, if inadequately treated wastewater were to be discharged to a stream or river, a eutrophic condition might develop within the aquatic environment due to the discharge of biodegradable oxygen-consuming materials. If this condition were sustained for an extended period of time, the ecological balance of the receiving stream, river or lake (i.e., aquatic microflora, plants and animals) would be upset. Continual depletion of the oxygen in these waters would also give rise to the development of obnoxious odors and unsightly scenes.

Knowledge of the characteristics of food and agricultural wastewater is essential to the development of economical and technically viable wastewater management systems that are in compliance with current environmental policy and regulations. Management methods that may have been adequate with other industrial wastewaters may be less feasible with food and agricultural wastewater, unless the methods are modified to reflect the characteristics of the

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Table 1.1 Wastewater treatment options available to remove various categories of pollutants in food and agricultural wastewater

Pollutants in wastewaters	Management options
Dissolved organic species	Biological treatment; adsorption; land applications; recovery and utilization.
Dissolved inorganic species	Ion exchange; reverse osmosis; evaporation/distillation; adsorption.
Suspended organic materials	Physicochemical treatment; biological treatment; land applications; recovery and utilization.
Suspended inorganic materials	Pretreatment (screen); Physicochemical treatment (sedimentation, flotation, filtration, coagulation).

wastewater and the opportunities it may hold. The wastewaters produced in agricultural processing and food processing vary in quantity and quality, with those streams from food processing typically having low strength and high volume, while those coming from animal farming operations tend to be high in strength but low in volume. These differences in quantity and quality dictate the type and capacity of wastewater management systems that should be deployed.

A clear understanding of the characteristics of food and agricultural wastewater permits management decision on treatment and utilization methods that are effective and economical, and this point is further spelt out in Table 1.1. For example, a low-strength and high-volume wastewater containing small amount of organic colloidal particulates may require a stand-alone biological wastewater treatment facility or a just a frame-and-plate filter press; the decision is both technical and economical. Another generalized observation is that the bulk oxygen-demanding substances are in the liquid phase for food processing wastewater, while most oxygen-demanding substances in the wastewater of a high-intensity livestock farming operation are in the form of solid particulates.

Some food processing operations occur seasonally (e.g., processing of fruits and vegetables). This seasonality adds complexity to the wastewater management systems that handle different sources of food and agricultural wastewater year round and, clearly, the understanding of wastewater characteristics helps plan ahead for such process operations. Knowledge of wastewater characteristics also allows strategic planning of water recycling and the reuse and recovery of valuable components in the wastewater.

As in most wastewaters, the components present in agricultural and food wastewater run a gamut of many undefined substances, almost all organic in nature. Organic matters are substances containing compounds comprised mainly of the elements carbon (C), hydrogen (H) and oxygen (O). The carbon atoms in the organic matter (also called carbonaceous compounds) may be oxidized both chemically and biologically to yield carbon dioxide (CO_2) and energy.

It is possible that some sources of wastewaters from certain food processing operations in a processing plant may have limited numbers of possible contaminants present. However, these wastewaters tend to mix with other streams of wastewaters from the same work site, making it virtually impossible to catalog all the substances in the effluents from the plant. Thus, the characteristics of agricultural and food wastewater can be viewed as a set of well-defined physicochemical and biological parameters that are critical in designing and managing agricultural and food wastewater treatment facilities.

1.1.1 General characteristics of wastewaters in agriculture and food processing

Wastewater from food processing operations is defined by the food itself. Food and agricultural wastewater contain dissolved organic solids from various operations and debris from mechanical processing of foods, such as peeling and trimming and hydrodynamic impacts in washing and transporting. Agricultural and food processing operations inevitably use large quantities of water to wash and, in some instances, cool food items. Canning wastewaters are essentially the same as home kitchen waste, as the wastewater is accumulated from various processes involved in the canning operations, such as trimming, sizing, juicing, pureeing, blanching, and cooking. Blanching of vegetables also requires large amounts of water to blanch and cool blanched vegetables. Almost all operation in food or agricultural processing involves cleaning of plant floors, machinery, and processing areas, often mixed with detergents that sometimes double as lubricants for the food processing machinery.

Depending on particular processing operations, water used in the operations is often reused, with or without treatment, when such practice is economical and legal. As fresh water supply is limited in many parts of the world, reusing water is often seen as a must for practical reasons. The reuse and recycling of water can result in considerable reduction in water usage. However, one should keep in mind that if the reused water is intended for edible food items, food safety issues arising from the reused water should be examined diligently and thoroughly. After all, food safety issues remain the overriding concern in all food processing and manufacturing operations.

Common pollutants present in the majority of food and agricultural wastewater and effluents from each stage of the typical wastewater treatment processes (see the following chapters for more information) include free and emulsified oil/grease, suspended solids, organic colloids, dissolved inorganic, acidity or alkalinity, and sludges. Table 1.1 is a summary of the processes available to treat food and agricultural wastewater.

Each food processing plant produces wastewaters of different quantity and quality. No two plants, even with similar processing capacity of food products, will generate wastewaters of the same quantity and quality, since there are too many variables (technical or otherwise) in the processes that ultimately define characteristics of wastewater. Furthermore, even different periods of food processing in the same plant may produce different wastewater streams with different characteristics. It is, therefore, essential to understand that the generalized description of wastewaters from fruit and vegetable processing needs to be understood as an approximate explanation of a complex issue. Any quantitative information shown here or anywhere else must be considered as averaged data. Typical characteristics, estimated volume, and estimated organic loading of wastewater generated by the food processing industry in the state of Georgia, USA, are shown in Table 1.2.

All major food and agricultural processing operations generate wastewater streams. However, the amount and strength of the wastewater streams varies with the major segments of the food and agricultural processing industry. Table 1.3 summarizes the sources of the wastewater streams and possible treatment processes.

As shown in Table 1.4, not all agro-food processing operations generate wastewater in such substantial quantities as to warrant on-site wastewater treatment facilities.

The following summary of the major segments of the agro-food processing operations requiring wastewater treatment is presented for the reader to appreciate the unique pollution issues therein, even though it is clear that there is considerable similarity among many segments of the food and agricultural processing industry. Additional information about the characteristics of wastewaters in all major segments of the food and agricultural processing industry can be found from Middlebrooks (1979).

Wastewaters from fruit and vegetable processing

The fruit and vegetable industries are as assorted as the names imply; these industries process the great variety of fruits and vegetables grown in the United States in a number of ways. The categories of processing include canning, freezing, dehydrating, and pickling and brining. The quantity and quality of wastewater streams from the industries vary considerably with the operations of the processing and the changing seasons.

Fruit and vegetable processing plants are major water users and waste generators. In all stages of food processing (unitary processes), raw foods must be

Table 1.2 Typical characteristics, estimated volume and estimated organic loading of wastewater generated by the food processing industry in Georgia, USA

Industry group	Estimated wastewater volume, million gallons/year	Typical characteristics	Estimated organic loading, tons/year BOD
Meat and poultry products	10,730	1,800 mg/L BOD 1,600 mg/L TSS 1,600 mg/L FOG 60 mg/L TKN	80,600
Dairy products	500	2,300 g/L BOD 1,500 mg/L TSS 700 mg/L FOG	14,900
Canned, frozen and preserved fruits and vegetables	2,080	500 mg/L BOD 1,100 mg/L TSS	4,300
Grain and grain mill products	130	700 mg/LBOD 1,000 mg/L TSS	300
Bakery products	530	2,000 mg/L BOD 4,000 mg/L TSS	4,400
Sugar and confectionery products	140	500 mg/L BOD	300
Fats and oils	350	4,100 g/L BOD 500 mg/L FOG	7,000
Beverages	3,660	8,500 mg/L BOD	91,000
Miscellaneous food preparations and kindred products	700	6,000 mg/L BOD 3,000 mg/L TSS	5,600
TOTAL	18,810		208,600

Abbreviations: TSS – total suspended solids; FOG – fats, oils, and grease.
Source: Magbunua (2000). Reproduced with permission of University of Georgia, College of Engineering, Outreach Service.

rendered clean and wholesome, and food processing plants must be maintained in a sanitary condition all of the time. Several common unit operations of fruit and vegetable processing that generate wastewater are shown in Figure 1.1.

Some of these unit operations shown in Figure 1.1 are intuitively obvious generators of waste (e.g., washing and rinsing), while others are less so (e.g., in-plant transport). Table 1.3 provides a brief explanation of several unitary processes that generate wastewater. For the most part, these wastewaters have been shown to be biodegradable, although salt is not generally removed during the treatment of olive storage or processing brines, cherry brines, and sauerkraut brines.

The effluents from fruit and vegetable processing operations consist mainly of carbohydrates such as sugars, starches, pectins, and other components of the cell walls that have been severed during processing. Of the total organic

Table 1.3 Summary of wastewater sources in major food and agricultural processing

Agro-food operations	Sources of wastewater streams	Treatment strategies
Vegetables and fruits	Sorting, trimming, washing, peeling, pureeing, in-plant transport, canning and retort, dehydration, and cleanup	Primary and secondary treatment processes
Fishery	Eviscerating, trimming, washing, pre-cooking, canning and retort, and cleanup	Primary and secondary treatment processes
Poultry and meat	Animal waste, killing and bleeding, scalding (poultry), eviscerating, washing, chilling, and cleanup	Primary and secondary treatment processes
Dairy	By-products, spills, leaks, line cleaning, and cleanup	Biological wastewater treatment
Corn wet milling	Steeping water, washing, and cleanup	Mainly screen, activated sludge processes, and secondary sedimentation
Sugar refining	Process water and cooling water	Recycling and discharge to municipal wastewater systems
Oil and fat	Steaming, solvent recovery, degumming, soapstock water, neutralization, and cleanup	Primary, secondary treatment, and sludge treatment processes
Non-alcoholic beverage	Cleanup	Discharge to municipal wastewater systems
Alcoholic beverage	Washing, cooling, leaks, and cleanup	Biological wastewater treatment and stabilization ponds
Flavoring extracts	Washing, evaporator condensate, steam distillation, and cleanup	Biological wastewater treatment or direct discharge to municipal wastewater systems
Egg product	Washing, leaks, and cleanup	Biological wastewater treatment and aerobic lagoon
Other food production	Leaks and cleanup	Depending on specific products and locality

matter, 70–80% is in the dissolved form and is not easily removed from wastewater by conventional mechanical means, although physicochemical processes may be used, such as adsorption and chemical oxidation or membrane-based technologies such as membrane filtration (see Chapter 3 for adsorption, chemical oxidation and membrane filtration). Obviously, biological wastewater treatment methods will work best in this type of wastewater streams.

Table 1.4 Common unitary processes of fruit and vegetable processing that generate wastewater

Process	Wastewater comes from …
Washing and rinsing	The entire process; may use detergent or chlorinated water.
Sorting (grading)	Density grading operation only.
In-plant transport	Water conveys products from one location to the other.
Peeling	Hot water or high-pressure water spray; may involve chemicals (caustic soda) or detergents.
Pureeing and juicing	Condensated evaporated water.
Blanching	Hot water or steam for blanching.
Canning and retort	Washing cans and steam for retort and cooling with water.
Drying or dehydration	Condensated evaporated water.
Mixing and cooking	Leaking of liquid products.
Clean-up	Cleaning up at every stage.

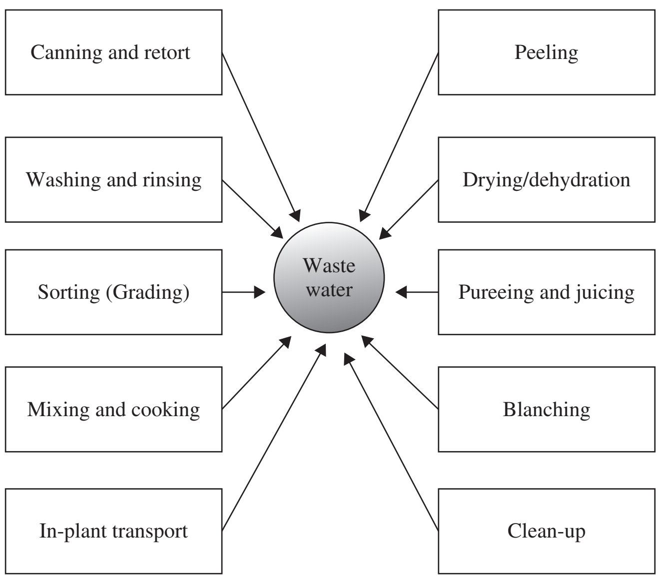

Figure 1.1 Unitary processes of fruit and vegetable processing that generate wastewater

The majority of the literature review regarding characterization of fruit and vegetable processing wastewaters focuses on wastewater streams from canning of fruits and vegetables (e.g., Soderquist *et al.*, 1975); the wastewaters from other processing operations of fruits and vegetables are of importance as well. Blanching of vegetables for freezing is a process that requires a large amount of water,

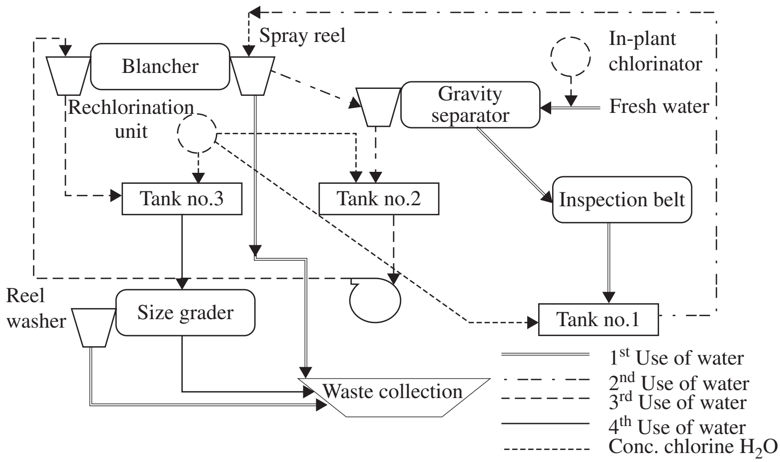

Figure 1.2 Diagram of a four-stage counterflow system for re-use of water in a pea cannery

and the quantity of wastewater generated is also proportionally high. Figure 1.2 shows a flow diagram of water reuse in a pea processing company.

Post-harvesting agricultural wastewater could also be a source of wastewater. Washing and rinsing waters used in cleaning fresh produces and fruits are sometimes reused, but wastewater is still generated in the process and has to be treated eventually. There is a possibility of recovering valuable substances from wastewater streams in fruit and vegetable processing, such as flavors from blanching waters. However, doing so is often technically complex and it may be economically impractical to extract these valuables from among a large number of undesirables in these streams using the technologies currently available.

Wastewaters from the fishery industry

The production processes used in the fishery industry generally include the following: harvesting; storing; receiving; eviscerating or butchering; pre-cooking; picking or cleaning; preserving; and packaging. Harvesting provides the basic raw materials (fish) for processing and subsequent distribution to the consumer. Once the fish are aboard the fishing vessel, the catch either is taken directly to the processor, or is iced or frozen for later delivery. Pre-processing may be carried out on board before the catch is sent to the processing plant. This may include beheading shrimp at sea, eviscerating fish or shellfish at sea, and other operations to prepare the fish for butchering. Wastes from the butchering and evisceration that are sizable are usually collected in dry form, or screened from the wastewater stream and processed as a fishery by-product.

The receiving operation usually involves unloading the vessel, weighing, and transporting by conveyor or suitable container to the processing area. The catch may be processed immediately or transferred to cold storage.

Sometimes, cooking or pre-cooking of crab and other shellfishes or tuna may be practiced in order to prepare the fish or shellfish for removal of meat and cleaning operation. The inedible fish or seafood parts, such as skin, bone, gills, shell, and similar, are easily removed after pre-cooking. The steam condensate, or stick water, from tuna or crab precook is often collected and further processed as a by-product. Wastes generated during this procedure are sometimes collected and saved for by-product processing. Depending on the species of seafoods, the cleaning operation may be either manual or mechanical.

With fresh fish or fresh shellfish, the meat product is packed into a plastic container and refrigerated for shipment to a distribution center or directly to a retail outlet. If shelf life of the product is required for an extended period of time before consumption, preservation techniques must be used to prevent spoilage from bacterial activities and enzymatic autolysis. Freezing, canning, pasteurization, drying, and refrigeration are the commonest preservation techniques used in the fishery industry.

Characteristics of fishery wastewaters are often dependent of several factors, including method of processing (mechanical or manual), fish species, and fish products. However, even with similar processing plants, using the same method of processing on the same species of fish and producing the same fish products, the quality of wastewaters (in terms of BOD, COD, TOC or TSS which will be explained later) varies with location and even with season. It should be mentioned that there is no substitute for direct determination of the quality of fishery wastewater in the effluent being investigated.

Like all wastewaters under consideration for treatment, the issue of treatability of seafood or fishery wastewater is often shaped by discharge limits set up by government agencies or an international body enforced through international treaties. Specifically, the discharge limits of BOD_5, Total Suspended Solids (TSS), and fat/oil/grease (FOG) are enforced based on the variety of fish species. Table 1.5 is a summary of discharge limits imposed by US EPA in 1985. It is prudent to consult with the local authorities on issues related to discharge limits of fishery wastewaters.

Fishery wastewaters are rich in fats and proteins. According to Middlebrooks (1979), a processing plant for finfish processing can produce 3.32 kg/ton of BOD, 0.348 kg/ton of grease/oil, and 1.42 kg/ton of suspended solids in the wastewater if using manual processing, or 11.9 kg/ton of BOD, 2.48 kg/ton grease/oil and 8.92 kg/ton of suspended solids in the wastewater if using mechanical means. This has generated a lot of interest in recovering these materials to offset totally or partially the costs of treating the fishery wastewater.

Table 1.5 Summary of discharge limits for the fishery industry imposed by the United States Environmental Protection Agency in 1985

Fish species	BOD_5	TSS	FOG
Tuna	20.0	8.3	2.1
Salmon	2.7	2.6	0.31
Other finfish	1.2	3.1–3.6	1.0–43
Crab	0.3–10	2.2–19	0.6–1.8
Shrimp	63–155	110–320	36–126
Clam and oyster	N/A	24–59	0.6–2.4

Source: USEPA.

Like proteins, the presence of fat/oil/grease (FOG) in the fishery wastewaters is mainly due to the processing of fishes. Canning, for example, generates grease and oil after fish products are heated.

Wastewaters from meat and poultry processing

The meat and poultry processing industry (excluding rendering but including seafood processing) uses an estimated 150 billion gallons of water annually. Although a portion of the water used by the industry is reused or recycled, most of it becomes wastewater. Similar to those wastewater streams from the fishery industry, the wastewaters from meat and poultry processing are high in fat/oil/grease and proteins.

The poultry industry handles billions of kilograms of chickens (called broilers, and with weights ranging from 1.1 kg to 2.0 kg) and turkeys each year, and processing plants vary, ranging from 50,000 birds to 250,000 birds per day. The main poultry operations involve receiving and storing, slaughtering, de-feathering, evisceration, packing, and freezing. Nearly all these operations involve using water, and a great deal of pollutants in the wastewater stream are created in the receiving and storing operation, where manure and unconsumed feed are washed down from the broilers. The water usage and wastewater generation is illustrated in Figure 1.3.

A meat processing plant consists of a slaughterhouse and/or a packing house. The slaughtering process has four basic operations: killing; hide removal/hog de-hairing; eviscerating/trimming; and cooling of carcasses (US EPA, 1974). Each of these operations contributes to the wastewater stream but, before being herded to their final destinations, the animals are held in the livestock holding pens, which generates additional wastewater streams. The wastewater streams from these holding pens primarily come from spillage from the water troughs, from cleanup, and from wastes laid by the animals.

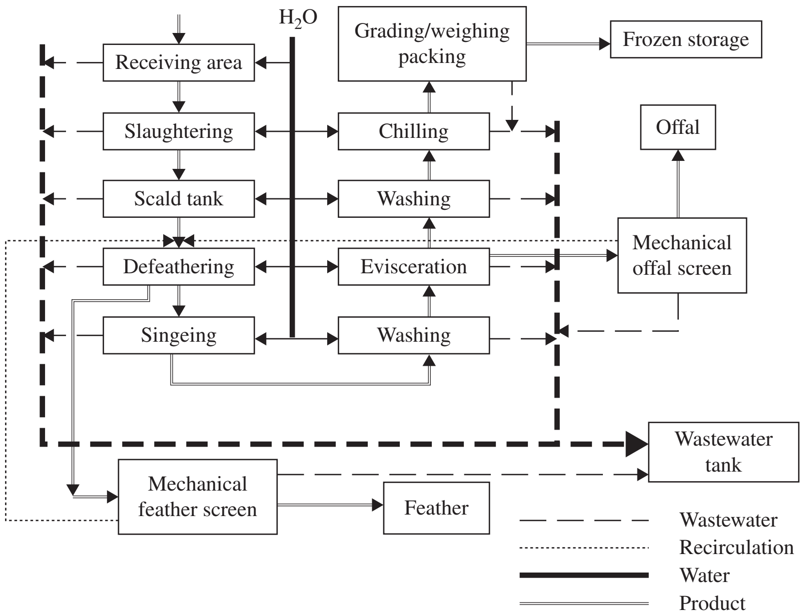

Figure 1.3 Flow chart of a poultry processing plant

Wastewaters from the dairy industry

The dairy industry is one of the most important agricultural processing industries in the United States, and it has grown steadily in recent decades.

Wastewaters originate from two major dairy processes – not only from fluid milk at the receiving station and bottling plants but, increasingly and more importantly, at the processing plants that produce condensed milk, powdered milk, condensed whey and other products such as dry whey, butter, cheese, cultured product, ice cream, and cottage cheese. The milk itself has a BOD_5 of 100,000 mg/L, and washing plants that produce butter and cheese may produce a wastewater with BOD_5 of 1,500–3,000 mg/L.

The dairy processing uses raw materials beyond milk and milk related materials; non-dairy ingredients, such as flavors, sugar, fruits, nuts, and condiments are utilized in manufacturing ice creams, yogurts, and flavored milks and frozen desserts. The pollutants can enter the wastewater streams through spills, leaks, and wasting of by-products. Apart from whey, which is acidic, most dairy wastewater streams are neutral or slightly alkaline, but they tend to become acidic rapidly due to the lactic acid produced as a result of the fermentation of lactose.

Most dairy product processing operations are multi-product facilities. Among these operations there may be receiving stations, bottling plants, creameries, ice cream plant, and cheese making plants; all these may contribute to wastewater streams in the dairy industry. Controlled products loss and recovery of by-products (e.g., whey protein) can improve not only yields (and thus profits), but also the amount and strength of dairy wastewater streams.

Dairy wastewaters are amendable to biological wastewater treatment, and this is the principal method used in the dairy industry. According to US EPA (1974), there were 64 activated sludge plants, 34 trickling filters, six aerobic lagoons, one stabilization pond, four combined systems, two anaerobic digestion facilities and one sand filtration for secondary effluent operating in the dairy industry in the United States. Most dairy processing plants treat their wastewaters to a level that is acceptable to municipal wastewater treatment facilities.

Wastewaters from oil and fat processing

Edible oil extraction involves solvent extraction of oil-bearing seeds or animal fats (there are mechanical expressers for olive oil and sesame oil) and refining steps of removing undesirables from extracted oil. In addition to cleanup and washing operations that use water, thus generating wastewater, several other processes all contribute to wastewater streams in edible oil production plants. These include deodorization that involves the injection of steam, refining that involves removing free fatty acids, phosphatides and other impurities with caustic soda, and oil recovery from the extracted meal using water.

The wastewaters from the oil production and refining industry, without doubt, are amendable to biological wastewater treatment. There are several pollutants in the wastewater streams from the edible oil extraction and refining, namely free and emulsified oils, grease, suspended solids, dissolved organic and inorganic solids. Along with the sludges that come from either primary or secondary treatment processes, many common wastewater treatment processes may be employed to remove these pollutants. Trace amounts of solvent such as hexane may be removed by adsorption or steam/air stripping. Another environmentally friendly method of removing hexane from wastewater is pervaporation (Peng *et al.*, 2003).

1.1.2 Parameters for physicochemical treatment of wastewater

pH

pH is a measurement of the acidity of the wastewater and an indication of growth conditions for the microbial communities used in biological wastewater treatment regimens. pH values vary greatly with the sources of agricultural and food wastewater, and also with the environmental conditions and duration of storage of the wastewater collected, as these factors dictate the amounts of certain substances and decomposition of biological matters, as well as emissions of ammonia compounds.

Solids content

Solids in wastewaters come in two forms: suspended solids (non-dissolvable) and dissolved solids. Suspended solids are nuisances, because they can either settle on the bottom of the receiving water body or float on the surface of the water body. Either way will affect the ecological balances of the receiving water body. Solids that readily settle are usually measured with an Imhoff cone (see Figure 1.1). Here, a known amount of water sample is poured into the cone and the amounts of the solids settled at given times are recorded and compared with the admissible amounts of settling solids in the wastewater for discharge. The acceptable settling solids level is usually determined by environmental regulations and, as a rule of thumb, discharge of wastewater or treated wastewater is not acceptable if the result of Imhoff testing shows that the water sample contains settling solids after ten minutes of testing.

Suspended solids are usually measured with a porous fiberglass filter of known pore size, in which a known amount of well-mixed water sample passes through. The dry mass accumulation on the filter is the amount of non-dissolvable solids.

Oils and greases represent another realm of suspended solids. These floating substances from some food operations have tendency to clog pipes and stick to the surfaces of any material. They are also easily oxidized, producing objectionable odors. In any case, oils and greases should be removed. The amount of oil and grease may be measured with the solvent extraction method found in the standard methods (Eaton *et al.*, 2005).

Soluble solids are laboratory measured, with evaporation and subsequent weighing of remaining dry mass of a known amount of water filtrate sample that is collected from the suspended solids measurement, or similar pre-treatment to remove suspended solids. Soluble solids are significant in some sources of food wastewater (e.g., fishery, dairy industries) and, thus, they are important in formulating wastewater treatment and resource recovery strategy.

Temperature

It is generally accepted that the temperature of wastewater discharged to a receiving water body cannot exceed 2–3°C of the ambient temperature, in order to maintain population balance of aquatic ecosystem of the receiving water body.

Wastewater from some food operations, such as retort, should be cooled before discharge or biological treatment.

Odor

Odor by itself is not a pollutant, although prolonged and intense exposure has been attributed to adverse effects on wastewater treatment plant workers and even residents living near the plant, with symptoms such as headache and nausea. Food wastewater contains significant amounts of organic matter and, when this organic matter decomposes into volatile amines, diamines and, sometimes, ammonia or hydrogen sulfide, odor results and it can be overwhelming.

The other source of wastewater odor generated in food processing is the blanching operation of certain sulfur-rich vegetables, such as cauliflowers and cabbage. The incentive for developing odor abatement strategy in food and agricultural wastewater management is obvious. The public perception and acceptance of a food processing plant are influenced often by nostril, not nostalgia.

1.1.3 Parameters for biological treatment of wastewater

The organic matters in food and agricultural wastewater are considerable and complex. Instead of attempting to identify each organic component of wastewater, wastewater professionals use the parameters for biological wastewater treatment to classify the organic materials. The most common parameters are the oxygen demand values. The term “oxygen demand” refers to the amount of oxygen that is needed to stabilize the organic content of the wastewater. The two most common oxygen demand methods of defining organic matters in wastewater are the *biochemical oxygen demand* and the *chemical oxygen demand*.

Biochemical oxygen demand

Biochemical oxygen demand is also known as its acronym, BOD, and it estimates the degree of organic content by measuring the oxygen required for the oxidation of organic matter by the aerobic metabolism of microbial communities. A characteristic simple carbonaceous compound is fructose, which is oxidized as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6O_2$$

The common procedures of BOD measurements are the dilution method and the respirometric method.

The dilution method is the most common method in use for wastewater industry. It consists of diluting a wastewater sample with a nutrient solution (to provide essential minerals for microbial activities) according to wastewater strength, within airtight bottles that are also saturated with air (for facilitating aerobic metabolism), and measuring the dissolved oxygen at the start and periodic intervals of the analysis. A five-day period is generally used, and the BOD measured thereafter is called BOD_5. The authoritative procedures of BOD analysis can be found in the standard methods (Eaton *et al*., 2005).

One cautionary note for BOD analysis is that the BOD analysis involves the degradation of organic matter by a microbial population in the testing bottles. The microbial count is important for the analysis, and insufficient microbial count will underestimate the BOD. This issue is particularly critical for food wastewater analysis, because some food processing operations involving thermal processing or other sterilizations, and the wastewater generated in those operations may not have sufficient microbial count for accurate analysis of BOD in the wastewater. A possible remedy for this is constantly to measure the wastewater from those operations for a long period of time or to add the adapted "seed" of bacteria to the wastewater. The dilution method is a time-honored but time-consuming method. An upgraded version of the method involves the use of a dissolved oxygen electrode in the form of BOD_5, enabling continuous readings of the dissolved oxygen during the five-day period. Commercial products of the BOD_5 analysis instruments based on the dilution method are available.

Another phenomenon that could alter the BOD analysis result, though not occurring in all food and agricultural wastewaters, is nitrification of the wastewater. Nitrification is a biochemical process of converting organic nitrogen (e.g., proteinaceous compounds) into nitrate (Liu *et al*., 2003). This is an aerobic process and, therefore, uses additional oxygen. One method of inhibiting nitrification is to use inhibitive chemicals such as allyl thiourea, methylene blue or 2-chloro-6-(trichloromethyl) pyridine (Metcalf & Eddy, Inc., 2002).

The respirometric method is an alternative to the dilution method in BOD analysis. It accelerates BOD analysis by combining biochemical processes with a faster chemical reaction. The basic design of the respirometric method is the use of a continuously stirred bottle with partially filled wastewater (and a headspace), which is connected to a reservoir of alkali (usually potassium chloride) that absorbs the CO_2 generated from the degradation of organic matters in the wastewater sample (see Figure 1.2). The pressure changes in the headspace of the BOD bottle are monitored constantly for consumption in O_2 in the wastewater sample. Even with the hybrid BOD analysis methods, the BOD analysis is slow and unsuitable for process control purposes in a wastewater treatment plant. Another approach to measuring the organic content of wastewater is chemical oxygen demand, which has been developed to complement the BOD analysis.

Chemical oxygen demand

Chemical oxygen demand (COD) is a method of estimating the total organic matter content of wastewaters, and is an approach that is based on the chemical oxidation of the organic materials in the wastewater. It involves either oxidation of the organic matters by permanganate or oxidation by potassium dichromate ($K_2Cr_2O_7$). COD analysis using dichromate is the most common method today, and it is used for continuous monitoring of biological wastewater treatment systems. The value of COD for a given wastewater stream is usually higher than that of BOD_5, due to the fact that inorganic matter can also be oxidized by potassium dichromate.

It is common to correlate the values of COD to the values of BOD_5, and to use the rapid COD analysis method (about two hours) to determine the organic content of the wastewater sample. The COD test utilizes $K_2Cr_2O_7$ in boiling concentrated sulfuric acid (150°C) in the presence of a silver catalyst (Ag_2SO_4) to facilitate the oxidation. The detailed procedures of COD test can be found in the standard methods (Eaton *et al.*, 2005). The following reaction describes the oxidation of organic carbonaceous compounds in the presence of $K_2Cr_2O_7$ and the catalyst:

$$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7\ H_2O$$

The COD is calculated by titrating the remaining dichromate of known amount or by spectrophotometrically measuring the Cr^{3+} ion at 606 nm (or remaining $Cr_2O_7^{2-}$ at 440 nm). Although it is more time-consuming, the titration method is more accurate than the spectrophotometry method.

A common interference in the COD testing is chloride in the wastewater, which is readily oxidized by dichromate:

$$Cr_2O_7^{2-} + 14H^+ + 6Cl^- \rightarrow 3\ Cl_2 + 2Cr^{3+} + 7\ H_2O$$

This interference that causes the COD level in the wastewater to be overestimated may be prevented with the addition of mercuric sulphate ($HgSO_4$) to remove Cl^- in the form of an $HgCl_2$ precipitate (Bauman, 1974). The above COD method is called "open reflux method" in the standard methods (Eaton *et al.*, 2005). Another COD testing method is called the closed reflux method (Eaton *et al.*, 2005). In this setting, the oxidation takes place in closed tubes filled with a small wastewater sample mixed with Ag_2SO_4 and $HgSO_4$. The tubes are heated to hasten the oxidation and, as a result, times are shorter. The COD is determined spectrophotometrically. Several commercial designs based on this method are available in the form of an apparatus or kit with solution ampoules and pre-measured reagents.

Total organic carbon

Total organic carbon (TOC) is a method based on the combustion of organic materials in the wastewater sample to CO_2 and water, dehydration of the combustion gases, and running the gases through an infrared analyzer. The analyzer reads out the amount of CO_2 from the combustion, which is proportional to the amount of carbon in the wastewater sample. Sometimes, the presence of inorganic carbon compounds in the wastewater, such as carbonates and bicarbonates, may distort TOC readings, but this problem may be eliminated by purging of inert gases.

Commercial TOC devices employ a different strategy, having two combustion tubes to accommodate combustions of inorganic carbon compounds at 150°C and organic carbon compounds at 950°C. The necessary use of a furnace in the TOC analysis renders this method more expensive, thus preventing TOC analysis from being widely used.

1.1.4 Nitrogen and phosphorous

The sources of nitrogen (N) and phosphorous (P) in food and agricultural wastewater may include chemical fertilizers, synthetic detergents used in cleaning food processing equipment, and metabolic compounds from proteinaceous materials. These elements are nutrients for microbial flora but, if they are present in excess, they may cause proliferation of algae in the receiving water body, with an adverse effect on the ecological balance. Increasingly, many wastewater treatment plants employ advanced wastewater treatment technologies to reduce or eliminate the amounts of nitrogen and phosphorous in the discharge.

1.1.5 Sampling

Accurate characterization of food and agricultural wastewater depends on accurate sampling of wastewater. Special attention should be paid to the representative sampling of a wastewater stream. Commercial sampling instruments are widely available, and simple in-house lab-scale continuous sampler can be set up with relatively modest means (Metcalf & Eddy, Inc., 2002). The procedure for a particular parameter of wastewater management may be found in the standard methods (Eaton *et al*., 2005).

1.2 Material balances and stoichiometry

In dealing with food and agricultural wastewater, whether formulating treatment and utilization strategy or planning the initial stage of a comprehensive management project, it is essential to have a basic understanding of the effects of mass flow rate or loading factors on process designs.

Stoichiometry is the material accounting for a chemical reaction. Given enough information, one can use stoichiometry to calculate masses, moles, and percents within a chemical equation that is an expression of a chemical process. Consider a simple reaction, where a reactant A converts into resultant B:

$$aA \rightarrow bB \tag{1.1}$$

where a and b are termed as stoichiometric coefficients and are thus positive proportionality constants.

Equation (1.1) tells us that for every a moles of reactant A consumed, there will be b moles of resultant B produced. If, initially, A has a mole concentration of N_{A0} and B has a starting concentration of N_{B0} then, at any given time, the reactant A and resultant B will be N_A and N_B. They are related to each other by the following expression:

$$(N_{A0}-N_A)/a = (N_B-N_{B0})/b \tag{1.2}$$

In this expression, $(N_{A0}-N_A)$ represents the consumption of A in moles at the time, while (N_B-N_{B0}) accounts for the gain of B in moles. Equation (1.2) may be used to calculate N_A or N_B when other terms in Equation (1.2) are known. For a more general chemical reaction with the following form:

$$aA + bB \rightarrow cC + dD \tag{1.3}$$

there will be

$$(N_{A0}-N_A)/a = (N_{B0}-N_B)/b = (N_C-N_{C0})/c = (N_D-N_{D0})/d \tag{1.4}$$

All terms in the equation are in moles.

Stoichiometric equations stipulate the important principle of mass conservation. Mass can neither be created nor be destroyed; it can only transform from one form or state to another. However, a stoichiometric expression can only provide a snapshot of the underlying chemical reaction at a given time; it does not reveal how fast the chemical reaction goes. For that attribute, we introduce a new term called “chemical reaction rate”. Consider the chemical reaction we used in Equation (1.1):

$$aA \rightarrow bB \tag{1.1}$$

In this case, we denote the rate of consumption of A per unit volume (molar unit) in a reactor as r_A and the rate of generation of B per unit volume in the reactor as r_B. We know by intuition and the stoichiometric equation:

$$b r_A = a r_B \tag{1.5}$$

It should be emphasized that all units discussed so far are mole-based. However, in many biological wastewater treatment process designs and calculations, the units are most likely mass-based. The relationship between mass based units and mole-based units is:

$$[\text{mole} - \text{based units}] = [\text{mass} - \text{based units}]/[\text{molecular weight}] \tag{1.6}$$

It is, however, difficult to establish the exact molecular structures of all microorganisms involved in a wastewater treatment process; therefore, mass-based units have to be used. In this scenario, stoichiometric equations cannot be used, and the relationship between reaction rates needs to be obtained from experiments.

Stoichiometry is a specific form of material balance for reactions and is expressed in mole-based units. In real-world situations, those reactions take place in reactors or other forms of containers. Their designs and layouts will affect the amounts of materials consumed and new substances generated in the reactions. Mass balance equations are used to describe macroscopically the dynamics of materials in a treatment system. We usually start developing mass balance equations on the treatment system with a control volume – a representative portion of the real system that can be integrated over the entire domain of the system. The changes of materials in the control volume should satisfy the law of mass conservation, i.e.:

$$[\text{species in}] - [\text{species out}] + [\text{generation}] = [\text{species accumulation}] \tag{1.7}$$

In mass units, Equation (1.7) can be expressed mathematically as:

$$m_{in} - m_{out} + r_A V_c = d(CV_c)/dt \tag{1.8}$$

Where:

m_{in} is the mass flow rate of species entering the control volume
m_{out} is the mass flow rate of species exiting the volume
V_c is the control volume
C is the mass concentration of the species.

With appropriate boundary conditions of the system, fluid flow characteristics and the initial condition of the species, Equation (1.8) can be integrated over these conditions to yield the quantities of the variables in the equation.

Equation (1.8) depicts an unsteady state system, where the amount of the species varies with the reaction time. For a steady state system, Equation (1.8) is reduced to:

$$m_{in} - m_{out} + r_A V_c = 0 \tag{1.9}$$

1.3 Fluid flow rate and mass loading

Almost all wastewater treatment plants are designed based on the annual average daily flow rate of wastewater being processed. However, it should be noted that every plant has to take into account the actual daily flow rate, characteristics of wastewater, and the combination of flow rate and composition (called mass-loading) of the wastewater steam. In an on-site wastewater treatment facility that deals with wastewater streams from a fixed food processing operation, flow rate and mass-loading are not complicated issues in designing and managing wastewater. However, for the wastewater streams from various sources subject to changes in flow rate and mass loadings, peak conditions (whether it is peak flow rate or mass loading) need to be considered as well.

1.4 Kinetics and reaction rates

Chemical or biochemical kinetics is the study of chemical or biochemical reactions with respect to reaction rates, the effect of conditions that reactions are subject to, re-arrangement of molecules, formation of intermediates, and involvement of catalyst. The word “kinetics,” originates from the Greek *kinesis*, meaning movement. Thus, kinetics of chemical or biochemical reactions mainly concern the rate of reaction and anything else affecting it.

In general, the reaction rate depends on the concentration of reactants. It may also depend on the concentrations of other species that do not appear in the stoichiometric equation. The dependence of reaction rate on concentrations of reactants can be expressed mathematically in terms of reaction rate constant and the powers of concentrations of reactants. For a general reaction form:

$$aA + bB \rightarrow cC + dD \tag{1.3}$$

The rate of reaction can be expressed as:

$$r = kC^{a}{}_{A}C^{b}{}_{B} \tag{1.10}$$

where:

k is the reaction rate constant

a and *b* are exponents that may or may not be equal to those coefficients appearing in Equation (1.3)

C_A and C_B are concentrations of reactants A and B.

The sum of *a* and *b* is called reaction order, i.e., reaction order for the reaction shown in Equation (1.3) is $(a + b)$. Generally, reactions are categorized as zero-order, first-order, second-order, or mixed-order (higher-order) reactions, based on the value of $(a + b)$. The unit of k is $(\text{concentration})^{1-a-b}$ $(\text{time})^{-1}$.

1.4.1 Zero-order reactions

Zero-order reactions (order = 0) have a constant rate. This rate is independent of the concentration of the reactants. The rate law is:

$$r = k$$

with k having the units of $(\text{concentration})^1$ $(\text{time})^{-1}$, e.g., M/sec.

1.4.2 First-order reactions

A first-order reaction (order = 1) has a rate proportional to the concentration of one of the reactants. A common example of a first-order reaction is the phenomenon of radioactive decay. The rate law is:

$$r = kC_A(\text{or } C_B \text{instead of } C_A), \text{with k having the units of } (\text{time})^{-1}, \text{e.g., sec}^{-1}.$$

1.4.3 Second-order reactions

A second-order reaction (order = 2) has a rate proportional to the concentration of the square of a single reactant or the product of the concentration of two reactants:

$$\text{rate} = kC_A{}^2(\text{or substitute B for A or k multiplied by the concentration of A times the concentration of B}), \text{with the unit of the rate constant } k = (\text{concentration})^{-1}(\text{time})^{-1}, \text{e.g., M}^{-1}\text{sec}^{-1}$$

1.4.4 Mixed-order or higher-order reactions

Mixed-order reactions, such as some biochemical reactions, have a fractional order for their rate. e.g.:

$$\text{rate} = kC_A^{1/3}$$

The unit of the rate constant k is $(\text{concentration})^{2/3}\ (\text{time})^{-1}$, e.g., $M^{2/3}/\text{sec}$.

1.4.5 Catalytic reactions

Almost all biochemical reactions involve catalysts – enzymes that are specialized proteins synthesized by microorganisms. A catalyst is a substance (enzyme for a biocatalyst) that increases the rate of reaction without undergoing *permanent* (bio)chemical change. The primary function of a catalyst is to lower the activation energy of a reaction, so that the reaction can be carried out easily, but not to affect the reaction equilibrium. In biochemical reactions, the enzyme is believed to possess certain active sites, consisting of amino acid side chains or functional groups, to which the specific functional groups of substrate molecules bind. Thus, the enzyme is reaction-specific. The active sites of the enzyme act as the donors or acceptors of electrons from the substrate molecules, and speed up the reaction. It is assumed that the enzymatic reaction involves a series of step-by-step elementary reactions forming complexes with substrate molecules along the way. It is described by Michaelis-Menten kinetics:

$$E + S \underset{k_{-1}}{\overset{k_1}{\longleftrightarrow}} ES \xrightarrow{k_2} E + P \tag{1.11}$$

The terms k_1, k_{-1} and k_2 are rate constants for, respectively, the association of substrate and enzyme, the dissociation of unaltered substrate from the enzyme and the dissociation of product (= altered substrate) from the enzyme. The overall rate of the reaction (r_P) is limited by the step ES to E + P, and this will depend on two factors: the rate of that step (i.e., k_2) and the concentration of enzyme that has substrate bound, i.e., C_{ES}:

$$r_P = k_2 C_{ES} \tag{1.12}$$

At this point, we make two assumptions. The first is the availability of a vast excess of substrate, so that $C_S \gg C_E$. The second is that it is assumed that the system is in pseudo-steady state, i.e., that the ES complex is being formed and broken down at the same rate, so that overall C_{ES} is constant. The formation of ES will depend on the rate constant k_1 and the availability of enzyme and substrate, i.e., C_E and C_S. The breakdown of C_{ES} can occur in two ways – either the conversion of substrate to product or the non-reactive dissociation of substrate from the complex. In both instances, the C_{ES} will be significant. Thus, at steady state, we can write:

$$k_1C_EC_S = (k_{-1} + k_2)C_{ES} \tag{1.13}$$

The term,

$$(k_{-1} + k_2)/k_1 = K_m \tag{1.14}$$

where K_m is called the Michaelis-Menten constant.

The total amount of enzyme in the system must be the same throughout the experiment, but it may either be free (unbound) E or in complex with substrate, C_{ES}. If we term the total enzyme C_{E0}, this relationship is expressed as:

$$C_{E0} = C_E + C_{ES} \tag{1.15}$$

in which C_{E0} represents initial enzyme concentration.

Inserting Equations (1.15) and (1.14) into Equation (1.13) and re-arranging the resulting equation lead to:

$$C_{ES} = C_{E0}C_S/(K_m + C_S) \tag{1.16}$$

So, substituting this right-hand side into Equation (1.12) in place of C_{ES} results in:

$$rp = k_2C_{E0}C_S/(K_m + C_S) \tag{1.17}$$

The maximum rate, which we can call r_{max}, would be achieved when all active sites of the enzyme molecules have saturated with substrate molecules. Under conditions when C_S is much greater than C_E, it is reasonable to assume that all C_E will be in the form C_{ES}. Therefore, $C_{E0} = C_{ES}$. We may substitute the term r_{max} for r and C_{E0} for C_{ES} in Equation (1.12), which would give us:

$$r_{max} = k_2C_{E0} \tag{1.18}$$

So, we now have:

$$rp = r_{max}C_S/(K_m + C_S) \tag{1.19}$$

This equation is commonly referred to as Michaelis-Menten equation.

The significance of Michaelis-Menten equation is that when r_p is half of r_{max}, from Equation (1.19), we would have

$$C_S = K_m \tag{1.20}$$

The K_m of the enzyme is the substrate concentration at which the reaction occurs at half of the maximum rate and is, therefore, an indicator of the affinity that the enzyme has for a given substrate and, hence, the stability of the enzyme-substrate complex. This interpretation may be better presented by plotting r_p versus C_S, which is called the Michaelis plot, shown in Figure 1.2.

It is obvious that, at low C_S, it is the availability of substrate that is the limiting factor. Therefore, as more substrate is added, there is a rapid increase in the initial rate of the reaction – any substrate is rapidly gobbled up and converted to product. At the K_m, 50% of active sites have substrate occupied. At higher C_S, a point is reached (at least theoretically) where all sites of the enzyme have substrate occupied. Adding more substrate will not increase the rate of the reaction; hence, the leveling-out observed in Figure 1.2.

In order to use the Michaelis-Menten equation, one needs to know the values of K_m and r_{max}. The common approach is to linearize the Michaelis-Menten equation by plotting $1/r_p$ versus $1/C_S$ (called Lineweaver-Burk linearization), which results in a slope of the linearized line, K_m/r_{max} and an intercept on the $1/r_p$ axis, $1/r_{max}$. Other linearization schemes of the Michaelis-Menten equation, such as Hanes-Wolf and Eadie-Hofstee plots, would accomplish the same objective as Lineweaver-Burk linearization.

1.5 Theoretical modeling and design of biological reactors

Theoretical modeling of biological wastewater reactors using mathematical equations allows engineers and designers to test their strategies and to evaluate their treatment options virtually, therefore reducing the amounts of time and money as well as the potential hazardous incidents that could happen to an actual experimentation. In an existing system, a robust model can be used to optimize the operational strategies. The development of the model often involves the selection of suitable equations that accurately describe fluid flow in the reactor and biochemical reactions in the form of microbial growth on organic and inorganic materials in the reactor. Many equations derived hereafter are more or less simplified equations of the generic reactor types.

This approach has its own advantages. First, it acknowledges that most biological reactors in use for wastewater treatment are quite similar to the generic reactors described below. Second, the methodologies of derivation of the equations for the generic reactors are valid for more "realistic" or complex reactors. Some of those equations related to reaction kinetics, mass balance, stoichiometry, and chemical thermodynamics have been explained previously. The overriding goal of this section is to combine fluid flow with kinetics in several geometrical environments of the generic reactor types in order to derive the reaction rate expressions and concentration profiles of substrates in the reactors. For the sake of simplicity, we focus on our attention initially to single reactions occurring in the liquid phase of constant density in single reactors.

1.5.1 Batch reactors

In a batch reactor, at any given time since the reactor starts, there is feed neither coming in nor coming out. The mass balance of a batch reactor from Equation (1.8) will be:

$$0 - 0 + r_A V_c = d(CV_c)/dt \tag{1.21}$$

For a constant volume, the above equation is:

$$r_A = dC_A/dt \tag{1.22}$$

This may be integrated from the initial concentration of A, C_{A0} to the final concentration C_{Af}, i.e.:

$$\int dt = t = \int dC_A/r_A \tag{1.23}$$

The exact relationship between r_A and C_A (kinetics) needs to be known in order to solve Equation (1.22) and establish the concentration history of reactant A.

For zero-order reactions (order = 0), r = k, so Equation (1.22) develops into:

$$t = \int dC_A/r_A = \int dC_A/k = (C_{A0} - C_{Af})/k \tag{1.24}$$

For first-order reactions (order = 1), $-r = kC_A$, so Equation (1.22) becomes:

$$t = \int dC_A/r_A = -\int dC_A/kC_A = \ln(C_{A0}/C_{Af})/k \tag{1.25}$$

For second-order reactions (order = 2), $-r = k(C_{B0} - C_{A0} + C_A)C_A$, so Equation (1.22) turns into:

$$C_{Af}/C_{A0} = (C_{Bf}/C_{B0}) \exp[-(C_{B0} - C_{A0})\, kt] \tag{1.26}$$

where:

$C_{Bf} = C_{Af} - C_{A0} + C_{B0}$
C_{B0} is the initial concentration of reactant B.

If $C_{A0} = C_{B0}$, $-r = kC^2_A$ and Equation (1.22) will yield

$$kt = 1/C_{Af} - 1/C_{A0} \quad (1.27)$$

1.5.2 Continuous stirred tank reactors (CSTRs)

Continuous stirred tank reactors (CSTRs) are widely used in biological wastewater treatment processes and can be schematically viewed as tanks with input and output, while a mechanical or pneumatic device provides the means of thorough mixing the liquid phase in tanks. In CSTRs, the liquid inside the reactor is completely mixed. The mixing is provided through an impeller, rising gas bubbles (usually oxygen) or both. The most characteristic feature of a CSTR is that it is assumed that the mixing is uniform and complete, such that the concentrations in any phase do not change with position within the reactor.

The dissolved oxygen in the tank is the same throughout the bulk liquid phase. Because of this uniformity of oxygen distribution in the reactor, a CSTR for wastewater treatment operations has the advantage of de-coupling the aerator or stirrer from the reaction as long as oxygen is well provided for (no need to consider pesky fluid mechanics), thus simplifying process design and optimization. Under the steady state, where all concentrations within the reactor are independent of time, we can apply the following materials balance on the reactor:

$$\begin{bmatrix}\text{Rate of addition}\\ \text{to reactor}\end{bmatrix} + \begin{bmatrix}\text{Rate of accumulation}\\ \text{within reactor}\end{bmatrix} = \begin{bmatrix}\text{Rate of removal}\\ \text{from reactor}\end{bmatrix} \quad (1.28)$$

Replacing the statements in the above expression with mathematical symbols leads to:

$$FC_{A0} + V_R r_A = FC_A \qquad F(C_{A0} - C_A) = -V_R r_A \quad (1.29)$$

where F is volumetric flow rate of feed and effluent liquid streams.

Re-arrangement of Equation (1.29) yields:

$$r_A = \frac{F}{V_R}(C_A - C_{A0}) = D(C_A - C_{A0}) \quad (1.30)$$

where $D = F/V_R$ and is called the dilution rate. The term characterizes the holding time or processing rate of the reactor under steady state condition. It is the number of full-tank volumes passing through the reactor tank per unit time and is equal to the reciprocal of the mean holding time of the reactor.

Because of lack of time dependence of concentrations in CSTR and, thus, the differential form of reactor analysis as in a batch reactor, CSTRs have the advantage of being well-defined, easily reproducible reactors. They are used frequently in many cell growth kinetics studies, despite relatively high cost and a long time for achieving steady state. Batch reactors, which can be as simple as sealed beakers or flasks used in an incubator shaker, are still widely used for their inexpensive, fast, and unbridled benefits.

No matter what type of reactors are used, the goal of studying cell growth kinetics should be based on the intended application and scope of the use of the kinetics. Only then may the experimental design and implementation be formulated.

1.6 Process economics

Process economics is the next step of a wastewater treatment and management design project, after preliminary selections of wastewater treatment processes have been completed in accordance with the project objectives. The economical considerations of the wastewater treatment and management project, including aspects of material and energy usage and recovery, are among the most important factors that influence the final decision about the project.

To develop meaningful cost estimates, the data from the wastewater characterization and other possible alternatives to the selected processes should be available. The cost estimates of the unit operations in wastewater treatment and management operations can be evaluated with the cost correlations developed by US EPA (1983). The cost correlations for alternative processes should also be gathered prior to the final estimation.

1.6.1 Capital costs

Capital costs usually refer to the process unit construction costs, the land costs, the costs of treatment equipment, financial costs in association with loan and services, costs of environmental impact or other community-imposed costs, and the costs of engineering, administration and contingencies.

1.6.2 Operational costs and facility maintenance

There are several important factors that determine the operational costs: energy costs, labor costs, materials and chemical costs, costs of transportation of treated sludge and treated wastewater, and discharge costs. The relative importance of these costs is highly dependent on locality and the quality of the influent and effluent of the wastewater treatment plant.

1.7 Further Reading

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