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Treatment of Dairy Processing Wastewaters

Trevor J. Britz and Corné van Schalkwyk
University of Stellenbosch, Matieland, South Africa

Yung-Tse Hung
Cleveland State University, Cleveland, Ohio, U.S.A.

1.1 INTRODUCTION

The dairy industry is generally considered to be the largest source of food processing wastewater in many countries. As awareness of the importance of improved standards of wastewater treatment grows, process requirements have become increasingly stringent. Although the dairy industry is not commonly associated with severe environmental problems, it must continually consider its environmental impact — particularly as dairy pollutants are mainly of organic origin. For dairy companies with good effluent management systems in place [1], treatment is not a major problem, but when accidents happen, the resulting publicity can be embarrassing and very costly.

All steps in the dairy chain, including production, processing, packaging, transportation, storage, distribution, and marketing, impact the environment [2]. Owing to the highly diversified nature of this industry, various product processing, handling, and packaging operations create wastes of different quality and quantity, which, if not treated, could lead to increased disposal and severe pollution problems. In general, wastes from the dairy processing industry contain high concentrations of organic material such as proteins, carbohydrates, and lipids, high concentrations of suspended solids, high biological oxygen demand (BOD) and chemical oxygen demand (COD), high nitrogen concentrations, high suspended oil and/or grease contents, and large variations in pH, which necessitates “specialty” treatment so as to prevent or minimize environmental problems. The dairy waste streams are also characterized by wide fluctuations in flow rates, which are related to discontinuity in the production cycles of the different products. All these aspects work to increase the complexity of wastewater treatment.

The problem for most dairy plants is that waste treatment is perceived to be a necessary evil [3]; it ties up valuable capital, which could be better utilized for core business activity. Dairy wastewater disposal usually results in one of three problems: (a) high treatment levies being charged by local authorities for industrial wastewater; (b) pollution might be caused when untreated wastewater is either discharged into the environment or used directly as irrigation water; and (c) dairy plants that have already installed an aerobic biological system are faced with the problem of sludge disposal. To enable the dairy industry to contribute to water conservation, an efficient and cost-effective wastewater treatment technology is critical.
Presently, plant managers may choose from a wide variety of technologies to treat their wastes. More stringent environmental legislation as well as escalating costs for the purchase of fresh water and effluent treatment has increased the impetus to improve waste control. The level of treatment is normally dictated by environmental regulations applicable to the specific area. While most larger dairy factories have installed treatment plants or, if available, dispose of their wastewater into municipal sewers, cases of wastewater disposal into the sea or disposal by means of land irrigation do occur. In contrast, most smaller dairy factories dispose of their wastewater by irrigation onto lands or pastures. Surface and groundwater pollution is, therefore, a potential threat posed by these practices.

Because the dairy industry is a major user and generator of water, it is a candidate for wastewater reuse. Even if the purified wastewater is initially not reused, the dairy industry will still benefit from in-house wastewater treatment management, because reducing waste at the source can only help in reducing costs or improving the performance of any downstream treatment facility.

1.2 DAIRY PROCESSES AND COMPOSITION OF DAIRY PRODUCTS

Before the methods of treatment of dairy processing wastewater can be appreciated, it is important to be acquainted with the various production processes involved in dairy product manufacturing and the pollution potential of different dairy products (Table 1.1). A brief summary of the most common processes [8] is presented below.

1.2.1 Pasteurized Milk

The main steps include raw milk reception (the first step of any dairy manufacturing process), pasteurization, standardization, deaeration, homogenization and cooling, and filling of a variety of different containers. The product from this point should be stored and transported at 4°C.

1.2.2 Milk and Whey Powders

This is basically a two-step process whereby 87% of the water in pasteurized milk is removed by evaporation under vacuum and the remaining water is removed by spray drying. Whey powder can be produced in the same way. The condensate produced during evaporation may be collected and used for boiler feedwater.

1.2.3 Cheese

Because there are a large variety of different cheeses available, only the main processes common to all types will be discussed. The first process is curd manufacturing, where pasteurized milk is mixed with rennet and a suitable starter culture. After coagulum formation and heat and mechanical treatment, whey separates from the curd and is drained. The finished curd is then salted, pressed, and cured, after which the cheese is coated and wrapped. During this process two types of wastewaters may arise: whey, which can either be disposed of or used in the production of whey powder, and wastewater, which can result from a cheese rinse step used during the manufacturing of certain cheeses.
1.2.4 Butter

Cream is the main raw material for manufacturing butter. During the churning process it separates into butter and buttermilk. The drained buttermilk can be powdered, cooled, and packed for distribution, or discharged as wastewater.

1.2.5 Evaporated Milk

The milk is first standardized in terms of fat and dry solids content after which it is pasteurized, concentrated in an evaporator, and homogenized, then packaged, sterilized, and cooled for storage. In the production of sweetened condensed milk, sugar is added in the evaporation stage and the product is cooled.

1.2.6 Ice Cream

Raw materials such as water, cream, butter, milk, and whey powders are mixed, homogenized, pasteurized, and transferred to a vat for ageing, after which flavorings, colorings, and fruit are added prior to freezing. During primary freezing the mixture is partially frozen and air is incorporated to obtain the required texture. Containers are then filled and frozen.

Table 1.1 Reported BOD and COD Values for Typical Dairy Products and Domestic Sewage

<table>
<thead>
<tr>
<th>Product</th>
<th>BOD₅ (mg/L)</th>
<th>COD (mg/L)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole milk</td>
<td>114,000</td>
<td>183,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>110,000</td>
<td>190,000</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>120,000</td>
<td>190,000</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>104,000</td>
<td>184,000</td>
<td>7</td>
</tr>
<tr>
<td>Skim milk</td>
<td>90,000</td>
<td>147,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>85,000</td>
<td>120,000</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>70,000</td>
<td>110,000</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>67,000</td>
<td>110,000</td>
<td>7</td>
</tr>
<tr>
<td>Buttermilk</td>
<td>61,000</td>
<td>134,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>75,000</td>
<td>110,000</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>68,000</td>
<td>100,000</td>
<td>7</td>
</tr>
<tr>
<td>Cream</td>
<td>400,000</td>
<td>750,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>400,000</td>
<td>860,000</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>400,000</td>
<td>840,000</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>399,000</td>
<td>800,000</td>
<td>7</td>
</tr>
<tr>
<td>Evaporated milk</td>
<td>271,000</td>
<td>378,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>208,000</td>
<td>370,000</td>
<td>7</td>
</tr>
<tr>
<td>Whey</td>
<td>42,000</td>
<td>65,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>45,000</td>
<td>80,000</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>40,000</td>
<td>80,000</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>34,000</td>
<td>80,000</td>
<td>7</td>
</tr>
<tr>
<td>Ice cream</td>
<td>292,000</td>
<td>500</td>
<td>7</td>
</tr>
<tr>
<td>Domestic sewage</td>
<td>300</td>
<td>500</td>
<td>4, 5</td>
</tr>
</tbody>
</table>

BOD, biochemical oxygen demand; COD, chemical oxygen demand.

Source: Refs. 4–7.
1.2.7 Yogurt

Milk used for yogurt production is standardized in terms of fat content and fortified with milk solids. Sugar and stabilizers are added and the mixture is then heated to 60°C, homogenized, and heated again to about 95°C for 3–5 minutes [9]. It is then cooled to 30–45°C and inoculated with a starter culture. For set yogurts, the milk base is packed directly and the retail containers are incubated for the desired period, after which they are cooled and dispatched. For stirred yogurts, the milk base is incubated in bulk after which it is cooled and packaged, and then distributed.

1.2.8 Wastewater from Associated Processes

Most of the water consumed in a dairy processing plant is used in associated processes such as the cleaning and washing of floors, bottles, crates, and vehicles, and the cleaning-in-place (CIP) of factory equipment and tanks as well as the inside of tankers. Most CIP systems consist of three steps: a prerinse step to remove any loose raw material or product remains, a hot caustic wash to clean equipment surfaces, and a cold final rinse to remove any remaining traces of caustic.

1.3 CHARACTERISTICS AND SOURCES OF WASTEWATER

The volume, concentration, and composition of the effluents arising in a dairy plant are dependent on the type of product being processed, the production program, operating methods, design of the processing plant, the degree of water management being applied, and, subsequently, the amount of water being conserved. Dairy wastewater may be divided into three major categories:

1. Processing waters, which include water used in the cooling and heating processes. These effluents are normally free of pollutants and can with minimum treatment be reused or just discharged into the storm water system generally used for rain runoff water.

2. Cleaning wastewaters emanate mainly from the cleaning of equipment that has been in contact with milk or milk products, spillage of milk and milk products, whey, pressings and brines, CIP cleaning options, and waters resulting from equipment malfunctions and even operational errors. This wastewater stream may contain anything from milk, cheese, whey, cream, separator and clarifier dairy waters [10], to dilute yogurt, starter culture, and dilute fruit and stabilizing compounds [9].

3. Sanitary wastewater, which is normally piped directly to a sewage works.

Dairy cleaning waters may also contain a variety of sterilizing agents and various acid and alkaline detergents. Thus, the pH of the wastewaters can vary significantly depending on the cleaning strategy employed. The most commonly used CIP chemicals are caustic soda, nitric acid, phosphoric acid, and sodium hypochlorite [10]; these all have a significant impact on wastewater pH. Other concerns related to CIP and sanitizing strategies include the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) contributions (normally <10% of total BOD concentration in plant wastewater), phosphorus contribution resulting from the use of phosphoric acid and other phosphorus-containing detergents, high water volume usage for cleaning and sanitizing (as high as 30% of total water discharge), as well as general concerns regarding the impact of detergent biodegradability and toxicity on the specific waste treatment facility and the environment in general [11].
Dairy industry wastewaters are generally produced in an intermittent way; thus the flow and characteristics of effluents could differ between factories depending on the kind of products produced and the methods of operation [12]. This also influences the choice of the wastewater treatment option, as specific biological systems have difficulties dealing with wastewater of varying organic loads.

Published information on the chemical composition of dairy wastewater is scarce [10]. Some of the more recent information available is summarized in Tables 1.2 and 1.3. Milk has a BOD content 250 times greater than that of sewage [23]. It can, therefore, be expected that dairy wastewaters will have relatively high organic loads, with the main contributors being lactose, fats, and proteins (mainly casein), as well as high levels of nitrogen and phosphorus that are largely associated with milk proteins [12,17]. The COD and BOD for whey have, for instance, been established to be between 35,000–68,000 mg/L and 30,000–60,000 mg/L, respectively, with lactose being responsible for 90% of the COD and BOD contribution [24].

1.4 TREATMENT OPTIONS

The highly variable nature of dairy wastewaters in terms of volumes and flow rates (which is dependent on the factory size and operation shifts) and in terms of pH and suspended solid (SS) content (mainly the result of the choice of cleaning strategy employed) makes the choice of an effective wastewater treatment regime difficult. Because dairy wastewaters are highly biodegradable, they can be effectively treated with biological wastewater treatment systems, but can also pose a potential environmental hazard if not treated properly [23]. The three main options for the dairy industry are: (a) discharge to and subsequent treatment of factory wastewater at a nearby sewage treatment plant; (b) removal of semisolid and special wastes from the site by waste disposal contractors; or (c) the treatment of factory wastewater in an onsite wastewater treatment plant [25,26]. According to Robinson [25], the first two options are continuously impacted by increasing costs, while the control of allowable levels of SS, BOD, and COD in discharged wastewaters are also becoming more stringent. As a result, an increasing number of dairy industries must consider the third option of treating industrial waste onsite. It should be remembered, however, that the treatment chosen should meet the required demands and reduce costs associated with long-term industrial wastewater discharge.

1.4.1 Direct Discharge to a Sewage Treatment Works

Municipal sewage treatment facilities are capable of treating a certain quantity of organic substances and should be able to deal with certain peak loads. However, certain components found in dairy waste streams may present problems. One such substance is fat, which adheres to the walls of the main system and causes sedimentation problems in the sedimentation tanks. Some form of onsite pretreatment is, therefore, advisable to minimize the fat content of the industrial wastewater that can be mixed with the sanitary wastewater going to the sewage treatment facility [6].

Dairy industries are usually subjected to discharge regulations, but these regulations differ significantly depending on discharge practices and capacities of municipal sewage treatment facilities. Sewer charges are based on wastewater flow rate, BOD₅ mass, SS, and total P discharged per day [10]. Some municipal treatment facilities may demand treatment of high-strength industrial effluents to dilute the BOD load of the water so that it is comparable to that of domestic sewage [7].
### Table 1.2  Chemical Characteristics of Different Dairy Plant Wastewaters

<table>
<thead>
<tr>
<th>Industry</th>
<th>BOD$_5$ (mg/L)</th>
<th>COD (mg/L)</th>
<th>pH</th>
<th>FOG (g/L)</th>
<th>TS (mg/L)</th>
<th>TSS (mg/L)</th>
<th>Alkalinity (mg/L as CaCO$_3$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheese</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cheese/whey plant</td>
<td>377–2214</td>
<td>189–6219</td>
<td>5.2</td>
<td>–</td>
<td>–</td>
<td>188–2330</td>
<td>–</td>
<td>13</td>
</tr>
<tr>
<td>Cheese factory</td>
<td>–</td>
<td>5340</td>
<td>5.22</td>
<td>–</td>
<td>4210</td>
<td>–</td>
<td>335</td>
<td>14</td>
</tr>
<tr>
<td>Cheese factory</td>
<td>–</td>
<td>2830</td>
<td>4.99</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15</td>
</tr>
<tr>
<td>Cheese processing industry</td>
<td>–</td>
<td>63,300</td>
<td>3.38</td>
<td>2.6</td>
<td>53,200</td>
<td>12,500</td>
<td>–</td>
<td>16</td>
</tr>
<tr>
<td>Cheese/casein product plant</td>
<td>–</td>
<td>5380</td>
<td>6.5</td>
<td>0.32</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15</td>
</tr>
<tr>
<td>Cheese/casein product plant</td>
<td>8000</td>
<td>–</td>
<td>4.5–6.0</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>17</td>
</tr>
<tr>
<td>Milk</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk/yogurt plant</td>
<td>–</td>
<td>4656</td>
<td>6.92</td>
<td>–</td>
<td>2750</td>
<td>–</td>
<td>546</td>
<td>14</td>
</tr>
<tr>
<td>Butter/milk powder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Butter/milk powder plant</td>
<td>–</td>
<td>1908</td>
<td>5.8</td>
<td>–</td>
<td>1720</td>
<td>–</td>
<td>532</td>
<td>14</td>
</tr>
<tr>
<td>Butter/milk powder plant</td>
<td>1500</td>
<td>–</td>
<td>10–11</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>17</td>
</tr>
<tr>
<td>Butter/Comte’cheese plant</td>
<td>1250</td>
<td>2520</td>
<td>5–7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>21</td>
</tr>
<tr>
<td>Whey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whey wastewater</td>
<td>35,000</td>
<td>–</td>
<td>4.6</td>
<td>0.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>17</td>
</tr>
<tr>
<td>Raw cheese whey</td>
<td>–</td>
<td>68,814</td>
<td>–</td>
<td>–</td>
<td>3190</td>
<td>1300</td>
<td>–</td>
<td>22</td>
</tr>
</tbody>
</table>

BOD, biological oxygen demand; COD, chemical oxygen demand; TS, total solids; TSS, total suspended solids; FOG, fats, oil and grease.
Table 1.3  Concentrations of Selected Elements in Different Dairy Wastewaters

<table>
<thead>
<tr>
<th>Industry</th>
<th>Total P (mg/L)</th>
<th>PO₄-P (mg/L)</th>
<th>TKN (mg/L)</th>
<th>NH₄-N (mg/L)</th>
<th>Na⁺ (mg/L)</th>
<th>K⁺ (mg/L)</th>
<th>Ca²⁺ (mg/L)</th>
<th>Mg²⁺ (mg/L)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheese/whey plants</td>
<td>29–181</td>
<td>6–35</td>
<td>14–140</td>
<td>1–34</td>
<td>263–1265</td>
<td>8.6–155.5</td>
<td>1.4–58.5</td>
<td>6.5–46.3</td>
<td>16</td>
</tr>
<tr>
<td>Cheese/whey plant</td>
<td>0.2–48.0</td>
<td>0.2–7.9</td>
<td>13–172</td>
<td>0.7–28.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>13</td>
</tr>
<tr>
<td>Cheese factory</td>
<td>45</td>
<td>–</td>
<td>102</td>
<td>–</td>
<td>550</td>
<td>140</td>
<td>30</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Cheese/casein product plant</td>
<td>85</td>
<td>–</td>
<td>140</td>
<td>–</td>
<td>410</td>
<td>125</td>
<td>70</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Cheese/casein product plant</td>
<td>100</td>
<td>–</td>
<td>200</td>
<td>–</td>
<td>380</td>
<td>160</td>
<td>95</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>Milk</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Butter/milk powder</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butter/milk powder plant</td>
<td>35</td>
<td>–</td>
<td>70</td>
<td>–</td>
<td>560</td>
<td>13</td>
<td>8</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Butter/Comité cheese plant</td>
<td>50</td>
<td>–</td>
<td>66</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>21</td>
</tr>
<tr>
<td>Whey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Whey wastewater</td>
<td>640</td>
<td>–</td>
<td>1400</td>
<td>–</td>
<td>430</td>
<td>1500</td>
<td>1250</td>
<td>100</td>
<td>17</td>
</tr>
<tr>
<td>Raw cheese whey</td>
<td>379</td>
<td>327</td>
<td>1462</td>
<td>64.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>22</td>
</tr>
</tbody>
</table>
In a recent survey conducted by Danalewich et al. [10] at 14 milk processing plants in Minnesota, Wisconsin, and South Dakota, it was reported that four facilities directed both their mixed sanitary and industrial wastewater directly to a municipal treatment system, while the rest employed some form of wastewater treatment. Five of the plants that treated their wastewater onsite did not separate their sanitary wastewater from their processing wastewater, which presents a major concern when it comes to the final disposal of the generated sludge after the wastewater treatment, since the sludge may contain pathogenic microorganisms [10]. It would thus be advisable for factories that employ onsite treatment to separate the sanitary and processing wastewaters, and dispose of the sanitary wastewater by piping directly to a sewage treatment facility.

1.4.2 Onsite Pretreatment Options

Physical Screening

The main purpose of screens in wastewater treatment is to remove large particles or debris that may cause damage to pumps and downstream clogging [27]. It is also recommended that the physical screening of dairy wastewater should be carried out as quickly as possible to prevent a further increase in the COD concentration as a result of the solid solubilization [28]. Wendorff [7] recommended the use of a wire screen and grit chamber with a screen aperture size of 9.5 mm, while Hemming [28] recommended the use of even finer spaced mechanically brushed or inclined screens of 40 mesh (about 0.39 mm) for solids reduction. According to Droste [27], certain precautionary measures should be taken to prevent the settling of coarse matter in the wastewater before it is screened. These requirements include the ratio of depth to width of the approach channel to the screen, which should be 1:2, as well as the velocity of the water, which should not be less than 0.6 m/sec. Screens can be cleaned either manually or mechanically and the screened material disposed of at a landfill site.

pH Control

As shown in Table 1.2, large variations exist in wastewater pH from different dairy factories. This may be directly attributed to the different cleaning strategies employed. Alkaline detergents generally used for the saponification of lipids and the effective removal of proteinaceous substances would typically have a pH of 10–14, while a pH of 1.5–6.0 can be encountered with acidic cleaners used for the removal of mineral deposits and acid-based sanitizers [11,29]. The optimum pH range for biological treatment plants is between 6.5 and 8.5 [30,31]. Extreme pH values can be highly detrimental to any biological treatment facility, not only for the negative effect that it will have on the microbial community, but also due to the increased corrosion of pipes that will occur at pH values below 6.5 and above 10 [6]. Therefore, some form of pH adjustment as a pretreatment step is strongly advised before wastewater containing cleaning agents is discharged to the drain or further treated onsite. In most cases, flow balancing and pH adjustment are performed in the same balancing tank. According to the International Dairy Federation (IDF) [30], a near-neutral pH is usually obtained when water used in different production processes is combined. If pH correction needs to be carried out in the balancing tank, the most commonly used chemicals are H2SO4, HNO3, NaOH, CO2, or lime [30].

Flow and Composition Balancing

Because discharged dairy wastewaters can vary greatly with respect to volume, strength, temperature, pH, and nutrient levels, flow and composition balancing is a prime requirement for
any subsequent biological process to operate efficiently [28]. pH adjustment and flow balancing can be achieved by keeping effluent in an equalization or balancing tank for at least 6–12 hours [7]. During this time, residual oxidants can react completely with solid particles, neutralizing cleaning solutions. The stabilized effluent can then be treated using a variety of different options.

According to the IDF [30], balance tanks should be adequately mixed to obtain proper blending of the contents and to prevent solids from settling. This is usually achieved by the use of mechanical aerators. Another critical factor is the size of the balance tank. This should be accurately determined so that it can effectively handle a dairy factory’s daily flow pattern at peak season. It is also recommended that a balancing tank should be large enough to allow a few hours extra capacity to handle unforeseen peak loads and not discharge shock loads to public sewers or onsite biological treatment plants [30].

Fats, Oil, and Grease Removal

The presence of fats, oil, and grease (FOG) in dairy processing wastewater can cause all kinds of problems in biological wastewater treatment systems onsite and in public sewage treatment facilities. It is, therefore, essential to reduce, if not remove FOG completely, prior to further treatment. According to the IDF [32], factories processing whole milk, such as milk separation plants as well as cheese and butter plants, whey separation factories, and milk bottling plants, experience the most severe problems with FOG. The processing of skim milk seldom presents problems in this respect.

As previously mentioned, flow balancing is recommended for dairy processing plants. An important issue, however, is whether the FOG treatment unit should be positioned before or after the balancing tank [32]. If the balancing tank is placed before the FOG unit, large fat globules can accumulate in the tank as the discharged effluent cools down and suspended fats aggregate during the retention period. If the balancing tank is placed after the FOG removal unit, the unit should be large enough to accommodate the maximum anticipated flow from the factory. According to the IDF [32], it is generally accepted that flow balancing should precede FOG removal. General FOG removal systems include the following.

**Gravity Traps.** In this extremely effective, self-operating, and easily constructed system, wastewater flows through a series of cells, and the FOG mass, which usually floats on top, is removed by retention within the cells. Drawbacks include frequent monitoring and cleaning to prevent FOG buildup, and decreased removal efficiency at pH values above 8 [32].

**Air Flotation and Dissolved Air Flotation.** Mechanical removal of FOG with dissolved air flotation (DAF) involves aerating a fraction of recycled wastewater at a pressure of about 400–600 kPa in a pressure chamber, then introducing it into a flotation tank containing untreated dairy processing wastewater. The dissolved air is converted to minute air bubbles under the normal atmospheric pressure in the tank [6,32]. Heavy solids form sediment while the air bubbles attach to the fat particles and the remaining suspended matter as they are passed through the effluent [6,9,25]. The resulting scum is removed and will become odorous if stored in an open tank. It is an unstable waste material that should preferably not be mixed with sludge from biological and chemical treatment processes since it is very difficult to dewater. FOG waste should be removed and disposed of according to approved methods [32]. DAF components require regular maintenance and the running costs are usually fairly high.

Air flotation is a more economical variation of DAF. Air bubbles are introduced directly into the flotation tank containing the untreated wastewater, by means of a cavitation aerator coupled to a revolving impeller [32]. A variety of different patented air flotation systems are available on the market and have been reviewed by the IDF [32]. These include the “Hydrofloat,” the “Robosep,” vacuum flotation, electroflotation, and the “Zeda” systems.
The main drawback of the DAF [25], is that only SS and free FOG can be removed. Thus, to increase the separation efficiency of the process, dissolved material and emulsified FOG solutions must undergo a physico-chemical treatment during which free water is removed and waste molecules are coagulated to form larger, easily removable masses. This is achieved by recirculating wastewater prior to DAF treatment in the presence of different chemical solutions such as ferric chloride, aluminum sulfate, and polyelectrolytes that can act as coalescents and coagulants. pH correction might also be necessary prior to the flotation treatment, because a pH of around 6.5 is required for efficient FOG removal [32].

Enzymatic Hydrolysis of FOG. Cammarota et al. [33] and Leal et al. [34] utilized enzymatic preparations of fermented babassu cake containing lipases produced by a *Penicillium restrictum* strain for FOG hydrolysis in dairy processing wastewaters prior to anaerobic digestion. High COD removal efficiencies as well as effluents of better quality were reported for a laboratory-scale UASB reactor treating hydrolyzed dairy processing wastewater, and compared to the results of a UASB reactor treating the same wastewater without prior enzymatic hydrolysis treatment.

1.4.3 Treatment Methods

Biological Treatment

Biological degradation is one of the most promising options for the removal of organic material from dairy wastewaters. However, sludge formed, especially during the aerobic biodegradation processes, may lead to serious and costly disposal problems. This can be aggravated by the ability of sludge to adsorb specific organic compounds and even toxic heavy metals. However, biological systems have the advantage of microbial transformations of complex organics and possible adsorption of heavy metals by suitable microbes. Biological processes are still fairly unsophisticated and have great potential for combining various types of biological schemes for selective component removal.

Aerobic Biological Systems. Aerobic biological treatment methods depend on microorganisms grown in an oxygen-rich environment to oxidize organics to carbon dioxide, water, and cellular material. Considerable information on laboratory- and field-scale aerobic treatments has shown aerobic treatment to be reliable and cost-effective in producing a high-quality effluent. Start-up usually requires an acclimation period to allow the development of a competitive microbial community. Ammonia-nitrogen can successfully be removed, in order to prevent disposal problems. Problems normally associated with aerobic processes include foaming and poor solid–liquid separation.

The conventional *activated sludge process* (ASP) is defined [35] as a continuous treatment that uses a consortium of microbes suspended in the wastewater in an aeration tank to absorb, adsorb, and biodegrade the organic pollutants (Fig. 1.1). Part of the organic composition will be completely oxidized to harmless endproducts and other inorganic substances to provide energy to sustain the microbial growth and the formation of biomass (flocs). The flocs are kept in suspension either by air blown into the bottom of the tank (diffused air system) or by mechanical aeration. The dissolved oxygen level in the aeration tank is critical and should preferably be 1–2 mg/L and the tank must always be designed in terms of the aeration period and cell residence time. The mixture flows from the aeration tank to a sedimentation tank where the activated sludge flocs form larger particles that settle as sludge. The biological aerobic metabolism mode is extremely efficient in terms of energy recovery, but results in large quantities of sludge being produced (0.6 kg dry sludge per kg of BOD₅ removed). Some of the sludge is returned to the aeration tank but the rest must be processed and disposed of in an environmentally acceptable.
manner, which is a major operating expense. Many variations of the ASP exist, but in all cases, the oxygen supplied during aeration is the major energy-consuming operation. With ASPs, problems generally encountered are bulking [17], foam production, precipitation of iron and carbonates, excessive sludge production, and a decrease in efficiency during winter periods.

Many reports show that ASP has been used successfully to treat dairy industry wastes. Donkin and Russell [36] found that reliable COD removals of over 90% and 65% reductions in total nitrogen could be obtained with a milk powder/butter wastewater. Phosphorus removals were less reliable and appeared to be sensitive to environmental changes.

Aerobic filters such as conventional trickling or percolating filters (Fig. 1.1) are among the oldest biological treatment methods for producing high-quality final effluents [35]. The carrier media (20–100 mm diameter) may consist of pumice, rock, gravel, or plastic pieces, which is populated by a very diverse microbial consortium. Wastewater from a storage tank is normally dosed over the medium and then trickles downward through a 2-m medium bed. The slimy microbial mass growing on the carrier medium absorbs the organic constituents of the wastewater and decomposes them aerobically. Sludge deposits require removal from time to time. Aerobic conditions are facilitated by the downward flow and natural convection currents resulting from temperature differences between the air and the added wastewater. Forced ventilation may be employed to enhance the decomposition, but the air must be deodorized by

Figure 1.1 Simplified illustrations of aerobic wastewater treatment processes: (a) aerobic filter, (b) activated sludge process (from Refs. 31, and 35–37).
passing through clarifying tanks. Conventional filters, with aerobic microbes growing on rock or gravel, are limited in depth to about 2 m, as deeper filters enhance anaerobic growth with subsequent odor problems. In contrast, filters with synthetic media can be fully aerobic up to about 8 m [37]. The final effluent flows to a sedimentation or clarifying tank to remove sludge and solids from the carrier medium.

It is generally recommended that organic loading for dairy wastewaters not exceed 0.28–0.30 kg BOD/m³ and that recirculation be employed [38]. A 92% BOD removal of a dairy wastewater was reported by Kessler [4], but since the BOD of the final effluent was still too high, it was further treated in an oxidation pond.

An inherent problem is that trickling filters can be blocked by precipitated ferric hydroxide and carbonates, with concomitant reduction of microbial activity. In the case of overloading with dairy wastewater, the medium becomes blocked with heavy biological and fat films. Maris et al. [39] reported that biological filters are not appropriate for the treatment of high-strength wastewaters, as filter blinding by organic deposition on the filter medium is generally found.

The rotating biological contactors (RBC) design contains circular discs (Fig. 1.2) made of high-density plastic or other lightweight material [35]. The discs, rotating at 1–3 rpm, are placed on a horizontal shaft so that about 40–60% of the disc surface protrudes out of the tank; this allows oxygen to be transferred from the atmosphere to the exposed films. A biofilm develops on the disc surface, which facilitates the oxidation of the organic components of the wastewater. When the biofilm sludge becomes too thick, it is torn off and removed in a sedimentation tank. Operation efficiency is based on the g BOD per m² of disc surface per day [35]. Rusten and his coworkers [40] reported 85% COD removal efficiency with an organic loading rate (OLR) of 500 g COD/m³ hour while treating dairy wastewater.

The RBC process offers several advantages over the activated sludge process for use in dairy wastewater treatment. The primary advantages are the low power input required, relative ease of operation and low maintenance. Furthermore, pumping, aeration, and wasting/recycle of solids are not required, leading to less operator attention. Operation for nitrogen removal is also relatively simple and routine maintenance involves only inspection and lubrication.

The sequencing batch reactor (SBR) is a single-tank fill-and-draw unit that utilizes the same tank (Fig. 1.2) to aerate, settle, withdraw effluent, and recycle solids [35]. After the tank is filled, the wastewater is mixed without aeration to allow metabolism of the fermentable compounds. This is followed by the aeration step, which enhances the oxidation and biomass formation. Sludge is then settled and the treated effluent is removed to complete the cycle. The SBR relies heavily on the site operator to adjust the duration of each phase to reflect fluctuations in the wastewater composition [41]. The SBR is seen as a good option with low-flow applications and allows for wider wastewater strength variations. Eroglu et al. [42] and Samkutty et al. [43] reported the SBR to be a cost-effective primary and secondary treatment option to handle dairy plant wastewater with COD removals of 91–97%. Torrijos et al. [21] also demonstrated the efficiency of the SBR system for the treatment of wastewater from small cheese-making dairies with treatment levels of >97% being obtained at a loading rate of 0.50 kg COD/m³ day. In another study, Li and Zhang [44] successfully operated an SBR at a hydraulic retention time (HRT) of 24 hours to treat dairy waste with a COD of 10 g/L. Removal efficiencies of 80% in COD, 63% in total solids, 66% in volatile solids, 75% Kjeldahl nitrogen, and 38% in total nitrogen, were obtained.

In areas where land is available, lagoons/ponds/reed beds (Fig. 1.2) constitute one of the least expensive methods of biological degradation. With the exception of aerated ponds, no mechanical devices are used and flow normally occurs by gravity. As result of their simplicity and absence of a sludge recycle facility, lagoons are a favored method for effective wastewater treatment. However, the lack of a controlled environment slows the reaction times, resulting in
long retention times of up to 60 days. Operators of sites in warmer climates may find the use of lagoons a more suitable and economical wastewater treatment option. However, the potential does exist for surface and groundwater pollution, bad odors, and insects that may become a nuisance.

Aerated ponds are generally 0.5–4.0 m deep [45]. Evacuation on the site plus lining is a simple method of lagoon construction and requires relatively unskilled attention. Floating aerators may be used to allow oxygen and sunlight penetration. According to Bitton [46], aeration for 5 days at 20°C in a pond normally gives a BOD removal of 85% of milk wastes. Facultative ponds are also commonly used for high-strength dairy wastes [47]. Although

Figure 1.2  Simplified illustrations of aerobic wastewater treatment processes: (a) sequencing batch reactor, (b) rotating biological contactor, (c) treatment pond (from Refs. 35, 40, 42, 45, 47–49).
ponds/lagoons are simple to operate, they are the most complex of all biologically engineered degradation systems [48]. In these systems, both aerobic and anaerobic metabolisms occur in addition to photosynthesis and sedimentation. Although most of the organic carbon is converted to microbial biomass, some is lost as CO₂ or CH₄. It is thus essential to remove sludge regularly to prevent buildup and clogging. The HRT in facultative ponds can vary between 5 and 50 days depending on climatic conditions.

Reed-bed or wetland systems have also found widespread application [49]. A design manual and operating guidelines were produced in 1990 [49,50]. Reed beds are designed to treat wastewaters by passing the latter through rhizomes of the common reed in a shallow bed of soil or gravel. The reeds introduce oxygen and as the wastewater percolates through it, aerobic microbial communities establish among the roots and degrade the contaminants. Nitrogen and phosphorus are thus removed directly by the reeds. However, reed beds are poor at removing ammonia, and with high concentrations of ammonia being toxic, this may be a limiting factor. The precipitation of large quantities of iron, manganese, and calcium within the reed beds will also affect rhizome growth and, in time, reduce the permeability of the bed. According to Robinson et al. [49], field studies in the UK have shown that reed beds have enormous potential and, in combination with aerobic systems, provide high effluent quality at reasonable cost.

Anaerobic Biological Systems. Anaerobic digestion (AD) is a biological process performed by an active microbial consortium in the absence of exogenous electron acceptors. Up to 95% of the organic load in a waste stream can be converted to biogas (methane and carbon dioxide) and the remainder is utilized for cell growth and maintenance [51,52]. Anaerobic systems are generally seen as more economical for the biological stabilization of dairy wastes [14], as they do not have the high-energy requirements associated with aeration in aerobic systems. Anaerobic digestion also yields methane, which can be utilized as a heat or power source. Furthermore, less sludge is generated, thereby reducing problems associated with sludge disposal. Nutrient requirements (N and P) are much lower than for aerobic systems [37], pathogenic organisms are usually destroyed, and the final sludge has a high soil conditioning value if the concentration of heavy metals is low. The possibility of treating high COD dairy wastes without previous dilution, as required by aerobic systems, reduces space requirements and the associated costs [53]. Bad odors are generally absent if the system is operated efficiently [51,54].

The disadvantages associated with anaerobic systems are the high capital cost, long start-up periods, strict control of operating conditions, greater sensitivity to variable loads and organic shocks, as well as toxic compounds [55]. The operational temperature must be maintained at about 33–37°C for efficient kinetics, because it is important to keep the pH at a value around 7, as a result of the sensitivity of the methanogenic population to low values [48]. As ammonia-nitrogen is not removed in an anaerobic system, it is consequently discharged with the digester effluent, creating an oxygen demand in the receiving water. Complementary treatment to achieve acceptable discharge standards is also required.

The anaerobic lagoon (anaerobic pond) (Fig. 1.3) is the simplest type of anaerobic digester. It consists of a pond, which is normally covered to exclude air and to prevent methane loss to the atmosphere. Lagoons are far easier to construct than vertical digester types, but the biggest drawback is the large surface area required.

In New Zealand, dairy wastewater [51] was treated at 35°C in a lagoon (26,000 m³) covered with butyl rubber at an organic load of 40,000 kg COD per day, pH of 6.8–7.2, and HRT of 1–2 days. The organic loading rate (OLR) of 1.5 kg COD/m³ day was on the low side. The pond’s effluent was clarified and the settled biomass recycled through the substrate feed. The clarified effluent was then treated in an 18,000 m³ aerated lagoon. The efficiency of the total system reached a 99% reduction in COD.
Completely stirred tank reactors (CSTR) [56] are, next to lagoons, the simplest type of anaerobic digester (Fig. 1.4). According to Sahm [57], the OLR rate ranges from 1–4 kg organic dry matter m$^{-3}$ day$^{-1}$ and the digesters usually have capacities between 500 and 700 m$^3$. These reactors are normally used for concentrated wastes, especially those where the polluting matter is present mainly as suspended solids and has COD values of higher than 30,000 mg/L. In the CSTR, there is no biomass retention; consequently, the HRT and sludge retention time (SRT) are not separated, necessitating long retention times that are dependent on the growth rate of the
slowest-growing bacteria involved in the digestion process. Ross [58] found that the HRT of the conventional digesters is equal to the SRT, which can range from 15–20 days.

This type of digester has in the past been used by Lebrato et al. [59] to treat cheese factory wastewater. While 90% COD removal was achieved, the digester could only be operated at a minimum HRT of 9.0 days, most probably due to biomass washout. The wastewater, consisting

![Simplified illustrations of anaerobic wastewater treatment processes: (a) conventional digester, (b) Contact digester, (c) fixed-bed digester (from Refs. 31, 57, 58, 60, 64, 66, 79).](image)

**Figure 1.4** Simplified illustrations of anaerobic wastewater treatment processes: (a) conventional digester, (b) Contact digester, (c) fixed-bed digester (from Refs. 31, 57, 58, 60, 64, 66, 79).
of 80% washing water and 20% whey, had a COD of 17,000 mg/L. While the CSTR is very useful for laboratory studies, it is hardly a practical option for full-scale treatment due to the HRT limitation.

The anaerobic contact process (Fig. 1.4) was developed in 1955 [60]. It is essentially an anaerobic activated sludge process that consists of a completely mixed anaerobic reactor followed by some form of biomass separator. The separated biomass is recycled to the reactor, thus reducing the retention time from the conventional 20–30 days to <1.0 days. Because the bacteria are retained and recycled, this type of plant can treat medium-strength wastewater (200–20,000 mg/L COD) very efficiently at high OLRs [57]. The organic loading rate can vary from 1 to 6 kg/m³ day COD with COD removal efficiencies of 80–95%. The treatment temperature ranges from 30–40°C. A major difficulty encountered with this process is the poor settling properties of the anaerobic biomass from the digester effluent. Dissolved air flotation [61] and dissolved biogas flotation techniques [62] have been attempted as alternative sludge separation techniques. Even though the contact digester is considered to be obsolete there are still many small dairies all over the world that use the system [63].

The upflow anaerobic filter (Fig. 1.3) was developed by Young and McCarty in 1969 [64] and is similar to the aerobic trickling filter process. The reactor is filled with inert support material such as gravel, rocks, coke, or plastic media and thus there is no need for biomass separation and sludge recycling. The anaerobic filter reactor can be operated either as a downflow or an upflow filter reactor with OLR ranging from 1–15 kg/m³ day COD and COD removal efficiencies of 75–95%. The treatment temperature ranges from 20 to 35°C with HRTs in the order of 0.2–3 days. The main drawback of the upflow anaerobic filter is the potential risk of clogging by undegraded suspended solids, mineral precipitates or the bacterial biomass. Furthermore, their use is restricted to wastewaters with COD between 1000 and 10,000 mg/L [58]. Bonastre and Paris [65] listed 51 anaerobic filter applications of which five were used for pilot plants and three for full-scale dairy wastewater treatment. These filters were operated at HRTs between 12 and 48 hours, while COD removal ranged between 60 and 98%. The OLR varied between 1.7 and 20.0 kg COD/m³ day.

The expanded bed and/or fluidized-bed digesters (Fig. 1.3) are designed so that wastewaters pass upwards through a bed of suspended media, to which the bacteria attach [66]. The carrier medium is constantly kept in suspension by powerful recirculation of the liquid phase. The carrier media include plastic granules, sand particles, glass beads, clay particles, and activated charcoal fragments. Factors that contribute to the effectiveness of the fluidized-bed process include: (a) maximum contact between the liquid and the fine particles carrying the bacteria; (b) problems of channeling, plugging, and gas hold-up commonly encountered in packed-beds are avoided; and (c) the ability to control and optimize the biological film thickness [57]. OLRs of 1–20 kg/m³ day COD can be achieved with COD removal efficiencies of 80–87% at treatment temperatures from 20 to 35°C.

Toldrá et al. [67] used the process to treat dairy wastewater with a COD of only 200–500 mg/L at an HRT of 8.0 hours with COD removal of 80%. Bearing in mind the wide variations found between different dairy effluents, it can be deduced that this particular dairy effluent is at the bottom end of the scale in terms of its COD concentration and organic load. The dairy wastewater was probably produced by a dairy with very good product-loss control and rather high water use [68].

The upflow anaerobic sludge blanket (UASB) reactor was developed for commercial purposes by Lettinga and coworkers at the Agricultural University in Wageningen, The Netherlands. It was first used to treat maize-starch wastewaters in South Africa [69], but its full potential was only realized after an impressive development program by Lettinga in the late 1970s [70,71]. The rather simple design of the UASB bioreactor (Fig. 1.3) is based on the superior
settling properties of a granular sludge. The growth and development of granules is the key to
the success of the UASB digester. It must be noted that the presence of granules in the UASB
system ultimately serves to separate the HRT from the solids retention time (SRT). Thus,
good granulation is essential to achieve a short HRT without inducing biomass washout. The
wastewater is fed from below and leaves at the top via an internal baffle system for separation of
the gas, sludge, and liquid phases. With this device, the granular sludge and biogas are separated.
Under optimal conditions, a COD loading of 30 kg/m³ day can be treated with a COD removal
efficiency of 85–95%. The methane content of the biogas is between 80 and 90% (v/v). HRTs of
as low as 4 hours are feasible, with excellent settling sludge and SRT of more than 100 days. The
treatment temperature ranges from 7–40°C, with the optimum being at 35°C.

Goodwin et al. [72] treated a synthetic ice cream wastewater using the UASB process at
HRTs of 18.4 hours and an organic carbon removal of 86% was achieved. The maximum OLR
was 3.06 kg total organic carbon (TOC) per m³ day. Cheese effluent has also been treated in the
UASB digester at a cheese factory in Wisconsin, USA [73]. The UASB was operated at
an HRT of 16.0 hours and an OLR of 49.5 kg COD/m³ day with a plant wastewater COD of
33,000 mg/L and a COD removal of 86% was achieved. The UASB digester was, however, only
a part of a complete full-scale treatment plant. The effluent from the UASB was recycled to a
mixing tank, which also received the incoming effluent. Although the system is described as an
UASB system, it could also pass as a separated or two-phase system, since some degree of pre-
acidification is presumably attained in the mixing tank. Furthermore, the pH in the mixing tank
was controlled by means of lime dosing when necessary. The effluent emerging from the mixing
tank was treated in an aerobic system, serving as a final polishing step, to provide an overall
COD removal of 99%.

One full-scale UASB treatment plant [51] in Finland at the Mikkeli Cooperative Dairy,
produces Edam type cheese, butter, pasteurized and sterilized milk, and has a wastewater
volume of 165 million liters per year. The digester has an operational volume of 650 m³, which
includes a balancing tank of 300 m³ [74,75]. The COD value was reduced by 70–90% and
400 m³ biogas is produced daily with a methane content of 70%, which is used to heat process
water in the plant.

One of the most successful full-scale 2000 m³ UASB described in the literature was in the
UK at South Caernarvon Creameries to treat whey and other wastewaters [76]. The whey alone
reached volumes of up to 110 kiloliters (KL) per day. In the system, which included a combined
UASB and aerobic denitrification system, COD was reduced by 95% and sufficient biogas was
produced to meet the total energy need of the whole plant. The final effluent passed to a
sedimentation tank, which removed suspended matter. From there, it flowed to aerobic tanks
where the BOD was reduced to 20.0 mg/L and the NH₃-nitrogen reduced to 10.0 mg/L. The
effluent was finally disposed of into a nearby river. The whey disposal costs, which originally
amounted to £30,000 per year, were reduced to zero; the biogas also replaced heavy fuel oil
costs. On full output, the biogas had a value of up to £109,000 per year as an oil replacement and
a value of about £60,000 as an electricity replacement. These values were, however, calculated
in terms of the oil and electricity prices of 1984, but this illustrates the economic potential of the
anaerobic digestion process.

The fixed-bed digester (Fig. 1.4) contains permanent porous carrier materials and by
means of extracellular polysaccharides, bacteria can attach to the surface of the packing material
and still remain in close contact with the passing wastewater. The wastewater is added either at
the bottom or at the top to create upflow or downflow configurations.

A downflow fixed-film digester was used by Canovas-Diaz and Howell [77] to treat
deproteinized cheese whey with an average COD of 59,000 mg/L. At an OLR of 12.5 kg COD/
m³ day, the digester achieved a COD reduction of 90–95% at an HRT of 2.0–2.5 days. The
deproteinized cheese whey had an average pH of 2.9, while the digester pH was consistently above pH 7.0 [78].

A laboratory-scale fixed-bed digester with an inert polyethylene bacterial carrier was also used by De Haast et al. [79] to treat cheese whey. The best results were obtained at an HRT of 3.5 days, with 85–87% COD removal. The OLR was 3.8 kg COD/m³ day and biogas yield amounted to 0.42 m³/kg CODadded per day. The biogas had a methane content of between 55 and 60%, and 63.7% of the calorific value of the substrate was conserved in the methane.

In a **membrane anaerobic reactor system** (MARS), the digester effluent is filtrated by means of a filtration membrane. The use of membranes enhances biomass retention and immediately separates the HRT from the SRT [68].

Li and Corrado (80) evaluated the MARS (completely mixed digester with operating volume of 37,850 L combined with a microfiltration membrane system) on cheese whey with a COD of up to 62,000 mg/L. The digester effluent was filtrated through the membrane and the permeate discharged, while the retentate, containing biomass and suspended solids, was returned to the digester. The COD removal was 99.5% at an HRT of 7.5 days. The most important conclusion the authors made was that the process control parameters obtained in the pilot plant could effectively be applied to their full-scale demonstration plant.

A similar membrane system, the anaerobic digestion ultrafiltration system (ADUF) has successfully been used in bench- and pilot-scale studies on dairy wastewaters [81]. The ADUF system does not use microfiltration, but rather an ultrafiltration membrane; therefore, far greater biomass retention efficiency is possible.

**Separated phase digesters** are designed to spatially separate the acid-forming bacteria and the acid-consuming bacteria. These digesters are useful for the treatment of wastes either with unbalanced carbon to nitrogen (C : N) ratios, such as wastes with high protein levels, or wastes such as dairy wastewaters that acidify quickly [51,68]. High OLRS and short HRTs are claimed to be the major advantages of the separated phase digester.

Burgess [82] described two cases where dairy wastewaters were treated using a separated phase full-scale process. One dairy had a wastewater with a COD of 50,000 mg/L and a pH of 4.5. Both digester phases were operated at 35 °C, while the acidogenic reactor was operated at an HRT of 24 hours and the methanogenic reactor at an HRT of 3.3 days. In the acidification tank, 50% of the COD was converted to organic acids while only 12% of the COD was removed. The OLR for the acidification reactor was 50.0 kg COD/m³ day, and for the methane reactor, 9.0 kg COD/m³ day. An overall COD reduction of 72% was achieved. The biogas had a methane content of 62%, and from the data supplied, it was calculated that a methane yield (YCH4/CODremoved) of 0.327 m³/kg CODremoved was obtained.

Lo and Liao [83,84] also used separated phase digesters to treat cheese whey. The digesters were described as anaerobic rotating biological contact reactors (AnRBC), but can really be described as tubular fixed-film digesters orientated horizontally, with internally rotating baffles. In the methane reactor, these baffles were made from cedar wood, as the authors contend that the desired bacterial biofilms develop very quickly on wood. The acidogenic reactor was mixed by means of the recirculation of the biogas. However, it achieved a COD reduction of only 4%. More importantly, the total volatile fatty acids concentration was increased from 168 to 1892 mg/L. This was then used as substrate for the second phase where a COD reduction of up to 87% was achieved. The original COD of the whey was 6720 mg/L, which indicates that the whey was diluted approximately tenfold.

Many other examples of two-phase digesters are found in the literature. It was the opinion of Kisaalita et al. [85] that two-phase processes may be more successful in the treatment of lactose-containing wastes. The researchers studied the acidogenic fermentation of lactose, determined the kinetics of the process [86], and also found that the presence of whey protein had
little influence on the kinetics of lactose acidogenesis [87]. Venkataraman et al. [88] also used a
two-phase packed-bed anaerobic filter system to treat dairy wastewater. Their main goals were
to determine the kinetic constants for biomass and biogas production rates and substrate
utilization rates in this configuration.

**Land Treatment**

Dairy wastewater, along with a wide variety of other food processing wastewaters, has been
successfully applied to land in the past [31]. Interest in the land application of wastes is also
increasing as a direct result of the general move of regulatory authorities to restrict waste disposal
into rivers, lakes, and the ocean, but also because of the high costs of incineration and landfiling
[89]. Nutrients such as N and P that are contained in biodegradable processing wastewaters make
these wastes attractive as organic fertilizers, especially since research has shown that inorganic
fertilizers might not be enough to stem soil degradation and erosion in certain parts of the world
[89,90]. Land application of these effluents may, however, be limited by the presence of toxic
substances, high salt concentrations, or extreme pH values [89]. It might be, according to
Wendorff [7], the most economical option for dairy industries located in rural areas.

**Irrigation**

The distribution of dairy wastewaters by irrigation can be achieved through spray nozzles over
flat terrain, or through a ridge and furrow system [7]. The nature of the soil, topography of the
land and the waste characteristics influence the specific choice of irrigation method. In general,
loamy well-drained soils, with a minimum depth to groundwater of 1.5 m, are the most suitable
for irrigation. Some form of crop cover is also desirable to maintain upper soil layer porosity
[31]. Wastewater would typically percolate through the soil, during which time organic
substances are degraded by the heterotrophic microbial population naturally present in the soil
[7]. An application period followed by a rest period (in a 1 : 4 ratio) is generally recommended.

Eckenfelder [31] reviewed two specific dairy factory irrigation regimes. The first factory
produced cream, butter, cheese, and powdered milk, and irrigated their processing wastewaters
after pretreatment by activated sludge onto coarse and fine sediments covered with reed and
canary grass in a 1 : 3 application/rest ratio. The second factory, a Cheddar cheese producer,
employed only screening as a pretreatment method and irrigated onto Chenango gravel with the
same crop cover as the first factory, in a 1 : 6 application/rest ratio.

Specific wastewater characteristics can have an adverse effect on a spray irrigation system
that should also be considered. Suspended solids, for instance, may clog spray nozzles and render
the soil surface impermeable, while wastewater with an extreme pH or high salinity might be
detrimental to crop cover. Highly saline wastewater might further cause soil dispersion, and a
subsequent decrease in drainage and aeration, as a result of ion exchange with sodium replacing
magnesium and calcium in the soil [31]. The land application of dairy factory wastewater, which
typically contains high concentrations of sodium ions, might thus be restricted [89]. And although
milk proteins and lactose are readily degradable by anaerobic bacteria naturally present in the soil,
FOG tends to be more resistant to degradation and will accumulate under anaerobic conditions [7].

According to Sparling et al. [15] there is little published information relating the effect that
long-term irrigation of dairy factory effluent may have on soil properties. Based on the irrigation
data Degens et al. [91] and Sparling et al. [15] investigated the effect that long-term dairy
wastewater irrigation can have on the storage and distribution of nutrients such as C, N, and P,
and the differences existing between key soil properties of a long-term irrigation site (22 years)
and a short-term irrigation site (2 years). Degens et al. [91] reported that irrigation had no effect
on total soil C in the 0–0.75 m layer, although redistribution of C from the top 0–0.1 m soil had
occurred, either as a result of leaching caused by the irrigation of highly alkaline effluents, or as a result of increased earthworm activity. The latter were probably promoted by an increased microbial biomass in the soil, which were mostly lactose and glucose degraders. It was also reported that about 81% of the applied P were stored in the 0–0.25 m layer compared to only 8% of the total applied N. High nitrate concentrations were measured in the groundwater below the site, and reduced nitrogen loadings were recommended in order to limit nitrogen leaching to the environment [91]. In contrast to the results reported by Degens et al. (2000) for a long-term irrigated site, Sparling et al. [15] found no redistribution of topsoil C in short-term irrigated soils, which was probably the result of a lower effluent loading. Generally, it was found that hydraulic conductivity, microbial content, and N-cycling processes all increased substantially in long-term irrigated soils. Since increases in infiltration as well as biochemical processing were noted in all the irrigated soils, most of the changes in soil properties were considered to be beneficial. A decrease in N-loading was, however, also recommended [15].

1.4.4 Sludge Disposal

Different types of sludge arise from the treatment of dairy wastewaters. These include: (a) sludge produced during primary sedimentation of raw effluents (the amounts of which are usually low); (b) sludge produced during the precipitation of suspended solids after chemical treatment of raw wastewaters; (c) stabilized sludge resulting from the biological treatment processes, which can be either aerobic or anaerobic; and (d) sludge generated during tertiary treatment of wastewater for final suspended solid or nutrient removal after biological treatment [92]. Primary sedimentation of dairy wastewater for BOD reduction is not usually an efficient process, so in most cases the settleable solids reach the next stage in the treatment process directly. An important advantage of anaerobic processes is that the sludge generated is considerably less than the amount produced by aerobic processes, and it is easier to dewater. Final wastewater polishing after biological treatment usually involves chemical treatment of the wastewater with calcium, iron, or aluminum salts to remove dissolved nutrients such as nitrogen and phosphorus. The removal of dissolved phosphorus can have a considerable impact on the amount of sludge produced during this stage of treatment [92].

The application of dairy sludge as fertilizer has certain advantages when compared to municipal sludge. It is a valuable source of nitrogen and phosphorous, although some addition of potassium might be required to provide a good balance of nutrients. Sludge from different factories will also contain different levels of nutrients depending on the specific products manufactured. Dairy sludge seldom contains the same pathogenic bacterial load as domestic sludge, and also has considerably lower heavy metal concentrations. The recognition of dairy sludge as a fertilizer does, however, depend on local regulations. Some countries have limited the amount of sludge that can be applied as fertilizer to prevent nitrates from leaching into groundwater sources [92].

According to the IDF [92], dairy sludge disposal must be reliable, legally acceptable, economically viable, and easy to conduct. Dairy wastewater treatment facilities are usually small compared to sewage treatment works, which means that thermal processes such as drying and incineration can be cost-prohibitive for smaller operations. It is generally agreed that disposal of sludge by land spraying or as fertilizer is the least expensive method. If the transport and disposal of liquid sludge cannot be done within reasonable costs, other treatment options such as sludge thickening, dewatering, drying, or incineration must be considered. Gravity thickeners are most commonly used for sludge thickening, while the types of dewatering machines most commonly applied are rotary drum vacuum filters, filter presses, belt presses, and decanter centrifuges [92].
1.5 POLLUTION PREVENTION

Reduction of wastewater pollution levels may be achieved by more efficiently controlling water and product wastage in dairy processing plants. Comparisons of daily water consumption records vs. the amount of milk processed will give an early indication of hidden water losses that could result from defective subfloor and underground piping. An important principle is to prevent wastage of product rather than flush it away afterwards. Spilled solid material such as curd from the cheese production area, and spilled dry product from the milk powder production areas should be collected and treated as solid waste rather than flushing them down the drain [6].

Small changes could also be made to dairy manufacturing processes to reduce wastewater pollution loads, as reviewed by Tetrapak [6]. In the cheese production area, milk spillage can be restricted by not filling open cheese vats all the way to the rim. Whey could also be collected sparingly and used in commercial applications instead of discharging it as waste.

Manual scraping of all accessible areas after a butter production run and before cleaning starts would greatly reduce the amount of residual cream and butter that would enter the wastewater stream. In the milk powder production area, the condensate formed could be reused as cooling water (after circulation through the cooling tower), or as feedwater to the boiler. Returned product could be emptied into containers and used as animal feed [6]. Milk and product spillage can further be restricted by regular maintenance of fittings, valves, and seals, and by equipping fillers with drip and spill savers. Pollution levels could also be limited by allowing pipes, tanks, and transport tankers adequate time to drain before being rinsed with water [8].

1.6 CASE STUDIES

1.6.1 Case Study 1

A summary of a case study as reported by Rusten et al. [93] is presented for the upgrading of a cheese factory additionally producing casein granules.

Background

The authors described how a wastewater treatment process of a Norwegian cheese factory, producing casein granules as a byproduct, was upgraded to meet the wastewater treatment demands set by large increases in production and stricter environmental regulations. The design criteria were based on the assumption that the plant produced an average amount of 150 m³/day of wastewater, which had an average organic load of 200 kg BOD/day with an average total phosphorous (TP) load of 3.5 kg TP/day and a pH range between 2 and 12.

Requirements

It was required that the treatment plant be able to remove more than 95% of the total BOD (>95% total COD). The specific amount of phosphorous that could be allowed in the discharged wastewater was still being negotiated with the authorities. The aim however, was to remove as much phosphorous as possible. The pH of the final effluent had to be between 6.5 and 8.0.

The Final Process

A flow diagram of the final process is summarized in Figure 1.5.
Process Efficiency
After modifications, the average organic load was 347 kg COD/day with average removal efficiency of 98% for both the total COD and the total phosphorous content. Extreme pH values in the incoming wastewater were also efficiently neutralized in the equalization tank, resulting in a 7.0–8.0 pH range in the reactors.

1.6.2 Case Study 2
A summary of a case study reported by Monroy et al. [94] is presented.

Background
As with the first case study, the authors reported on how an existing wastewater treatment system of a cheese manufacturing industry in Mexico, which was operating below the consents, could be upgraded so that the treated wastewater could meet the discharge limits imposed by local environmental authorities. The factory produced an average wastewater volume of 500 m³/day with an average composition (mg/L) of 4430 COD, 3000 BOD₅, 1110 TSS, and 754 FOG.

Requirements
Environmental regulations required the treated wastewater to have less than 100 mg/L BOD, 300 mg/L COD, 100 mg/L TSS, and 15 mg/L FOG. The pH of the discharged effluent had to be between 6.0 and 9.0. The old treatment system was not effective enough to reduce the BOD, COD, TSS, and FOG to acceptable levels, although the final pH of 7.5 was within the recommended range. The factory was looking for a more effective treatment system that could utilize preexisting installations, thereby reducing initial investment costs, and also have low operation costs.

The Final Process
A flow diagram of the final process is summarized in Figure 1.6.
Pollution levels in the raw wastewater were first reduced by initiating an “in-factory” wastewater management program, which resulted in greater pH stability and lower phosphorous levels (by recycling certain cleaning chemicals and substituting others) as well as reduced levels of salt (by concentrating and drying brine). The modified wastewater treatment process resulted in an overall removal efficiency of 98% BOD (final concentration = 105 mg/L), 96% COD (final concentration = 225 mg/L), 98% TSS (final concentration = 24 mg/L), and 99.8% FOG (final concentration = 1.7 mg/L). The modifications ultimately resulted in a total operating cost increase of 0.4% at the factory.

1.6.3 General Conclusions: Case Studies

All wastewater treatment systems are unique. Before a treatment strategy is chosen, careful consideration should be given to proper wastewater sampling and composition analysis as well as a process survey. This would help prevent an expensive and unnecessary or overdesigned treatment system [95]. A variety of different local and international environmental engineering firms are able to assist in conducting surveys. These firms can also be employed to install effective patented industrial-scale installations for dairy processing wastewater treatment.

1.7 CONCLUSIONS

As management of dairy wastes becomes an ever-increasing concern, treatment strategies will need to be based on state and local regulations. Because the dairy industry is a major water user and wastewater generator, it is a potential candidate for wastewater reuse. Purified wastewater can be utilized in boilers and cooling systems as well as for washing plants, and so on. Even if the purified wastewater is initially not reused, the dairy industry will still benefit directly from in-house wastewater treatment, since levies charged for wastewater reception will be significantly reduced. In the United Kingdom, 70% of the total savings that have already been achieved with anaerobic digestion are due to reduced discharge costs [96]. The industry will also benefit where effluents are currently used for irrigation of pastures, albeit in a more indirect way. All these facts underline the need for efficient dairy wastewater management.

Before selecting any treatment method, a complete process evaluation should be undertaken along with economic analysis. This should include the wastewater composition, concentrations, volumes generated, and treatment susceptibility, as well as the environmental impact of the solution to be adopted. All options are expensive, but an economic analysis...
may indicate that slightly higher maintenance costs may be less than increased operating costs. What is appropriate for one site may be unsuitable for another.

The most useful processes are those that can be operated with a minimum of supervision and are inexpensive to construct or even mobile enough to be moved from site to site. The changing quantity and quality of dairy wastewater must also be included in the design and operational procedures. From the literature it appears as if biological methods are the most cost-effective for the removal of organics, with aerobic methods being easier to control, but anaerobic methods having lower energy requirements and lower sludge production rates. Since no single process for treatment of dairy wastewater is by itself capable of complying with the minimum effluent discharge requirements, it is necessary to choose a combined process especially designed to treat a specific dairy wastewater.

REFERENCES


