Biology and Engineering of Animal Wastewater Lagoons

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Introduction

Wastewater treatment lagoons are earthen impoundments that are engineered and constructed to treat as well as temporarily store wastewater. In practice, the terms *lagoons and ponds* are used interchangeably. The wastewater treatment lagoons are different from wastewater storage or holding lagoons in that they are designed to function as biological reactors that allow effective degradation of organic compounds contained in the wastewater by various microorganisms. Through the biodegradation process, solid particles in the wastewater are broken down and liquified, and organic compounds are converted into inorganic compounds, resulting a reduced organic content in the wastewater effluent. Meanwhile, organic nutrients, such as nitrogen and phosphorus, are mineralized into inorganic nutrients in the forms of ammonia and orthophosphate, respectively. If designed and opereated properly, treatment lagoons are capable of achieving siginificant reduction of suspended solids and mineralization of nturients in the wastewater, which is desirable for wastewater irrigation and reuse.

The physical, chemical, and biological environments in the treatment lagoons are controlled to achieve the intended purposes of wastewater treatment. Depending on the specific designs, some treatment lagoons are built with wastewater storage volumes as well as treatment volumes. In comparison, wastewater storage lagoons are designed only to provide the temporary storage of wastewater. Even though natural degradation of the wastewater by indigenous microorganisms does occur during the storage period, the waste degradation rate in a storage lagoon is not controlled, and therefore degradation is less efficient and often unpredictable. Treatment lagoons are not pumped down below their treatment volume elevation except for maintenance purposes whereas storage lagoons are emptied regularly when the wastewater is pumped out for irrigation.

Wastewater treatment lagoons have been widely used for the treatment of human, industrial, and animal wastewaters due to their low capital costs and simple operational and maintenance requirements compared with other biological treatment systems. In the United States, use of treatment lagoons for human waste has the longest history, about 100 years. At present, the lagoons are mainly used in small community and rural areas where sufficient land areas are available. Animal wastewater lagoons have about 30 years of history. Early animal wastewater lagoons were designed primarily based on the experiences with human wastewater lagoons. After years of experimental evaluations, agricultural engineers and scientists have gained a better understanding of the biochemistry involved and have developed engineering design standards specific to animal wastewater lagoons. Due to the high contents of nutrients and organics in the animal wastewater, the treatment capacity of wastewater lagoons is often limited, and effluent from the lagoons is not suitable for direct discharge into surface waters. In this paper, I will discuss the biology/biochemistry and the engineering designs of animal wastewater lagoons.

Biology/Biochemistry of Wastewater Lagoons

Wastewater treatment lagoons range in depth from shallow to deep and often are categorized by their mode of biodegradation, as determined by the presence or absence of dissolved oxygen (aerobic or anaerobic), source of oxygen, and other design features. Biological degradation and sedimentation are the primary means for removal of organic and inorganic compounds from the wastewater in the lagoons. Based on the presence of oxygen, the lagoons are classified as aerobic, anaerobic, and facultative lagoons. Bacteria are the primary microorganisms responsible for waste degradation in all types of lagoons. Algae live symbiotically with bacteria in aerobic and facultative lagoons and play an important role in removing nutrients from the wastewater.

Aerobic lagoons

Aerobic lagoons contain dissolved oxygen in the water to sustain aerobic bacteria. The dissolved oxygen can be supplied naturally or artificially. Natural aeration is achieved by air diffusion at the water surface, by wind- or thermal gradient-induced mixing, and by photosynthesis. The photosynthetic microorganisms include algae and cyanobacteria (blue-green algae). Artificial aeration is achieved by mechanical aeration. Thus, there are two types of aerobic lagoons, naturally aerated lagoons and mechanically aerated lagoons.

Naturally aerated lagoons are quite shallow, typically 1 to 2 feet, to allow sunlight to penetrate the full lagoon depth to maintain active algal photosynthetic activity during daylight hours. The oxygen produced from the photosynthesis process is used by aerobic bacteria to degrade the organic waste. The dissolved oxygen level in the lagoon increases and decreases throughout the day, depending on the solar irradiation available. The general chemical reaction for aerobic degradation of organic compounds is as follows:

Organics compounds (C, H, O, N, S) + O_2 —> $CO_2 + H_2O + NH_4^+$ (or NO_3^-) + S (or SO_4^{2-})

Natural air diffusion and algal photosynthesis require that naturally aerated lagoons be shallow and have large surface areas. Mechanically aerated lagoons (Figure 1), however, do not have the depth requirement. They are usually built with much more depth and a smaller surface areas than the naturally aerated lagoons. Since oxygen is supplied through mechanical means, algal photosynthesis in the mechanically aerated lagoons plays an insignificant role.

Under aerobic conditions, the nitrogenous compounds (proteins, peptides, and amino acids) are first converted to ammonium (NH_4^+) by heterotrophic bacteria. If sufficient oxygen is available and the chemical environment is right, nitrification bacteria may be established and oxidize ammonium into nitrite and then into nitrate. Therefore, the end products of nitrogen oxidation can be ammonium, nitrite, or nitrate, depending on how complete the oxidation is carried out by the bacteria. Organic carbon is oxidized into carbon dioxide. Sulfur compounds (sulfur-containing protein) in the wastes are converted to elemental sulfur (S) or sulfate (SO_4^{2-}) in the aerobic environment instead of odor-causing sulfides in the anaerobic environment. The degree of oxidation depends on the amount of oxygen provided and the reaction time allowed in the treatment process.

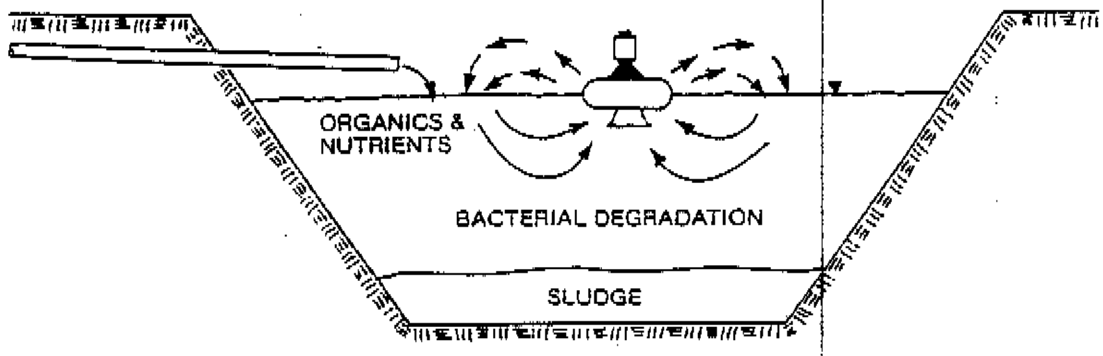

Figure 1. Mechanically aerated lagoons (adapted from NZAEI, 1984)

Facultative lagoons

The facultative lagoons are deeper than aerobic lagoons, varying in depth from 5 to 8 feet. Waste is treated by bacterial action occurring in an upper aerobic layer, a facultative middle layer, and a lower anaerobic layer. Aerobic bacteria degrade the waste in the upper layer where oxygen is provided by natural surface aeration and algal photosynthesis. Settleable solids are deposited on the lagoon bottom and degraded by anaerobic bacteria. The facultative bacteria in the middle layer degrade the waste aerobically whenever dissolved oxygen is present and anaerobically otherwise. Figure 2 shows microbial interactions and waste degradation pathways in a facultative lagoon. The facultative lagoons are more common than naturally aerated lagoons. They have more depth and smaller surface areas but still have good odor control capabilities because of the presence of the upper aerobic layer, where odorous compounds such as sulfides produced by the anaerobic degradation in the lower layer, are oxidized before emission into the atmosphere. Biochemical reactions in the facultative lagoons are a combination of aerobic and anaerobic degradation reactions.

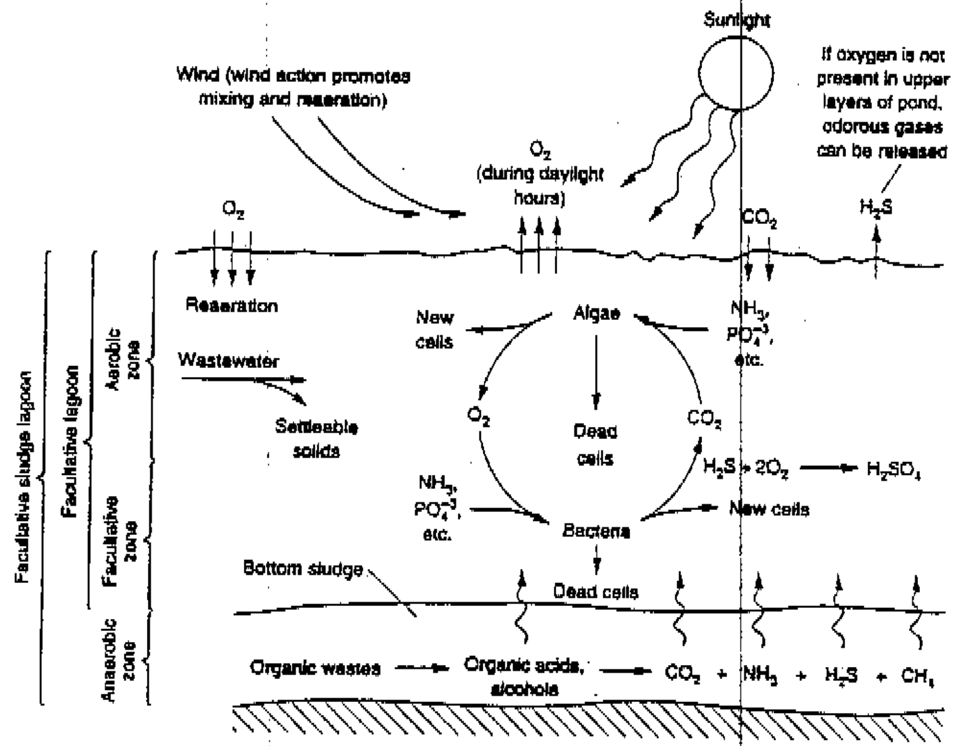

Figure 2. Facultative lagoons (adapted from Crites and Tchobanoglous, 1998).

Anaerobic lagoons

Anaerobic lagoons are used mostly for high-strength wastewater treatment, such as animal wastewater. They vary in depth from 8 to 30 feet and are built as deep as the local geography allows to minimize the surface area and reduce odor emissions. The top layer may contain dissolved oxygen depending on wind, temperature, and organic loading rate. In general, however, the aerobic layer is very thin, less than 50 cm. and the contribution of aerobic bacteria to the overall waste degradation is insignificant. Due to the high organic content of animal wastewater, all the primary lagoons used for animal wastewater treatment are essentially anaerobic lagoons, unless mechanical aeration is added to artificially render the lagoons facultative or aerobic.

Under anaerobic conditions, two distinct reactions occur. In stage one, hydrolysis of organic compounds and conversion to intermediate organic acids are achieved by acid-forming bacteria called acidogens. Then in stage two, the organic acids are converted by methane and carbon dioxide by methane-forming bacteria called methanogens as illustrated in Figure 3.

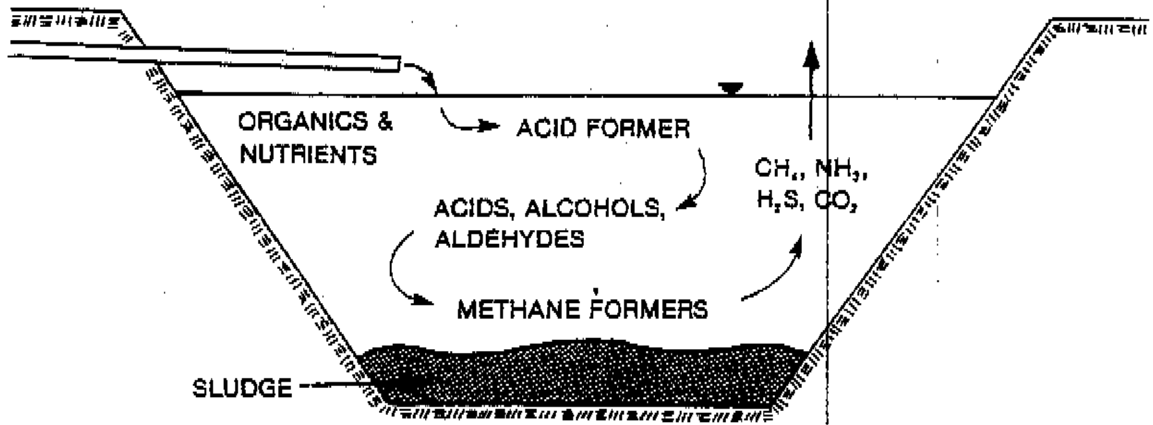

Figure 3. Degradation of organic compounds in anaerobic lagoons (adapted from NZAEI, 1984).

The overall complete reaction of anaerobic degradation is:

$$\text{Organics(C, H, O, N, S)} \longrightarrow CH_4 + CO_2 + NH_4^+ + H_2S$$

Methane (CH_4) and carbon dioxide (CO_2) are produced as the end products of organic carbon degradation. Methane has very low solubility in water and is readily emitted into the atmosphere as soon as it is formed. Ammonium (NH_4^+) and hydrogen sulfide are the end products of nitrogen and sulfur degradation, respectively. Ammonium (NH_4^+) exists in equilibrium with ammonia (NH_3) in the wastewater. Carbon dioxide, ammonia, and hydrogen sulfide are three soluble gases. Their potential for emission into the atmosphere is largely dependent on the pH and temperature of the lagoon water. A high pH (>8) favors more ammonia emissions while a low pH (<6) favors more hydrogen sulfide and carbon dioxide emissions. Between the two major groups of anaerobic bacteria (acidogens and methanogens), methanogens are more environmentally sensitive and fastidious. They have stricter pH and redox potential requirements. They are obligate anaerobes, i.e., they can not tolerate any molecular or ionic oxygen in the water. The redox potential of water must be below –300 for the methanogens to thrive. The optimum pH for methanogens is 6.8 to 7.5, with the lowest pH being 6.2. In comparison, acidogens are more versatile and have much wider working pH range, 5 to 8, with the optimum level being 5 to 6. Therefore, one way to suppress the methane production in anaerobic lagoons is to control the pH below 6.2. However, when methanogens are suppressed, the anaerobic degradation will not be carried to completion, yielding much organic acids that may cause strong odor problems. Volatile fatty acid (VFA) in the lagoon water has been used by researchers as an indicator for measuring how complete the anaerobic degradation is in anaerobic digesters and lagoons and for correlation with odor levels. A well functioning anaerobic digester usually has a VFA below 800 mg/L. In comparison, a heavily loaded anaerobic lagoon can have a VFA above 3,000 mg/L. The exact correlation of VFA with odor level from anaerobic lagoons has not been well established by researchers. It is currently a researchable question.

In most anaerobic lagoons, anaerobic degradation is not complete due to the fact that conditions such as organic loading rate, temperature, and retention time are not optimum for bacterial reactions. High concentrations of intermediate degradation compounds, such as organic acids, amino acids, aldehydes, sulfides and others are present in the lagoon water and contribute most of the foul odors. Well-designed and operated lagoons can effectively lower the concentrations of these odorous compounds and keep odors to a minimum. However, high emissions of methane from open lagoons may be expected. Gases produced at the bottom of anaerobic lagoons often lift sludge to the top surface forming a layer of floating solids. Adding gental mechanical mixing in the anaerobic lagoons has been found to help prevent this solids-rising phenomena (Rice, 1977). Covering lagoons is a good way to recover the methane gas as a fuel and also to control emissions of ammonia and other odorous gases.

In addition to acidogens and methanogens, other types of bacteria also live in the anaerobic lagoons. One with particular environmental significance is purple sulfur bacteria. Lagoons containing such bacteria turn pink, purple, or red in the warm months. Purple sulfur bacteria are phototropic anaerobic bacteria that use sunlight as an energy source and are capable of oxidizing sulfides, therefore reducing odors from anaerobic lagoons. Due to their capability of suppressing odors from the anaerobic lagoons, they have recently become the subject of research. Research is underway at several universities to understand the right conditions for growth of purple sulfur bacteria in the lagoons. The USDA-ARS and University of Nebraska researchers (Gilley et al., 2000) have found that the zinc in swine diets enhanced the growth of purple sulfur bacteria, whereas copper inhibited their growth. Temperature and solar radiation are other factors that affect the growth of purple sulfur bacteria.

Even though lagoons are generally considered to be simple treatment systems, the biology and biochemistry involved are very complex, involving many forms of biological reactions. Anaerobic lagoons are mostly suitable for treating animal wastewater. Facultative and aerobic lagoons may be used as secondary lagoons after the anaerobic lagoons to provide further biological degradation and produce relatively odor-free water for recycling and irrigation. Thus, different types of lagoons can be combined into multiple-stage lagoons to achieve the best treatment if the land area is available. Since they are operated at ambient temperature, lagoons function well only in mild or warm climates.

Design and Engineering of Lagoons

As mentioned earlier, lagoons are designed to be bioreactors that should provide suitable environmental conditions for microorganisms to degrade the organic wastes. Major factors affecting the performance of animal wastewater lagoons include temperature, organic loading rate, retention time, pH, and the presence of inhibitory or toxic chemicals. Ammonia is one of the chemicals that needs special consideration. At high concentrations, ammonia can become inhibitory or toxic to the bacteria in the lagoons. Generally, total ammonia nitrogen in the lagoon water should be kept under 1,500 mg/L. Therefore, animal manure needs sufficient dilution to reduce the ammonia concentration to a safe level before entering the lagoons.

Lagoons are sized based on organic loading rate or retention time. Organic loading rate and retention time are related to the temperature of the lagoons, which in turn are decided by the local climatic conditions. The allowable organic loading rate is higher for the lagoons located in warmer climates. According to the current engineering design standard published by American Society of Agricultural Engineers (ASAE) and the design method published by USDA-NRCS, the organic loading rate of lagoons is defined as follows. For anaerobic lagoons, the organic loading rate is the volumetric loading rate of volatile solids, which is the amount of volatile solids in pounds loaded per 1,000 cubic feet of lagoon treatment volume per day (lb VS/1000 ft^3.day). For facultative and naturally aerated lagoons, the organic loading rate is the area-loading rate of 5-day biochemical oxygen demand (BOD_5), which is the amount of BOD_5 in pounds per acre of surface area per day (lb BOD_5/ac.day).

ASAE has an engineering design standard for anaerobic lagoons (ASAE, 1999). USDA-NRCS also has an engineering design standard (USDA-NRCS, 1992). Each design standard has a set of organic loading rates recommended for different regions of the United States, with higher values for warmer regions. However, the two sets of the organic loading rates show different values for the same regions. For example, for California from the south to the north, the ASAE standard recommends the maximum loading rate to be 5.5 to 4.5 lbVS/1000 ft^3.day, while the USDA standard recommends 6.5 to 5.5 lbVS/1000 ft^3.day. Since the ASAE standard is the most recent standard developed and the authors are from USDA-NRCS, it is recommended that the ASAE standard be used as the first reference. Figure 4 shows the loading rate of anaerobic lagoons for the different regions of the United States as published by ASAE. In either standard, the organic loading rate is given as the recommended maximum loading rate. The actual loading rate that should be used depends on the treatment objectives being stressed, such as maximizing pollutant reduction, reducing odors, or minimizing sludge production. The ASAE standard recommends a minimum 50-day retention time for primary anaerobic lagoons. Figure 5 shows a diagram of a single-stage anaerobic lagoon, which contains wastewater treatment volume and storage volume.

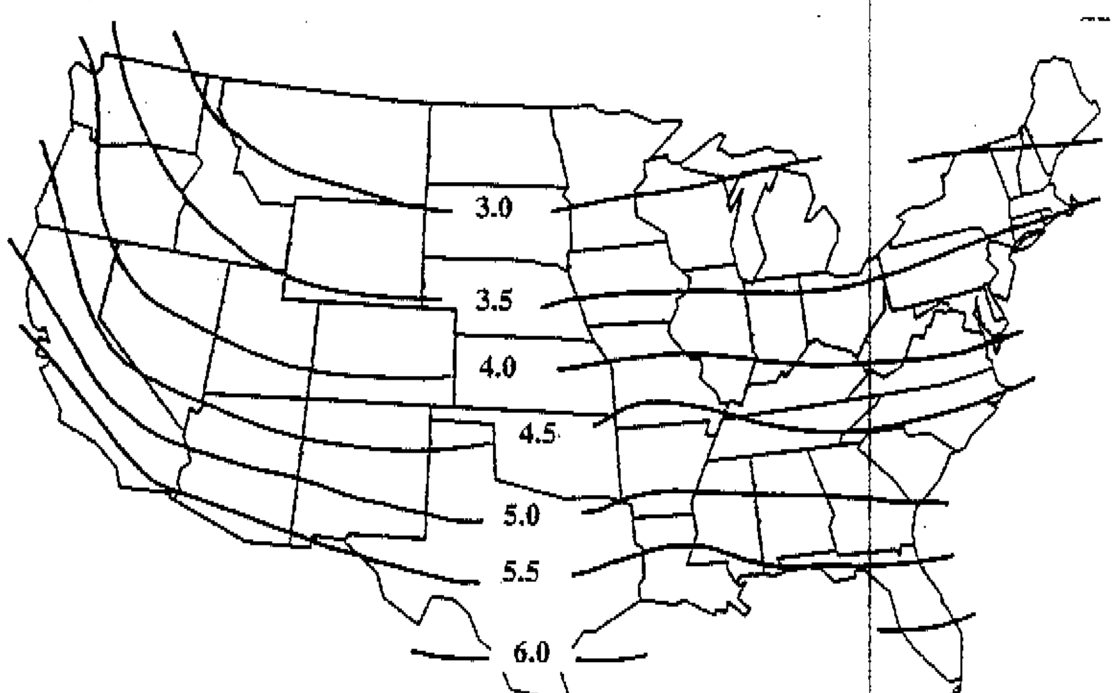

Figure 4. Loading rate of anaerobic lagoons in lb/1000 ft^3.day (adapted from ASAE, 1999).

Figure 5. Anaerobic lagoon cross section (adapted from USDA-NRCS, 1992).

Two-stage anaerobic lagoons are sized based on the criteria that the first stage contains the treatment volume and the second stage contains the storage volume. Both stages must have the volumes for net precipitation and 25-year/24 hour storm on the lagoon surface and freeboard. If wastewater is recycled on the farm for manure flushing systems, a two-stage lagoons is recommended over a single-stage lagoon. The recycling wastewater should be pumped from the second-stage..

The detailed design procedures for anaerobic lagoons are given in both the ASAE Standards and USDA-NRCS Design Method. The ASAE Standards list various engineering considerations for construction of lagoons, including sitting, groundwater protection, depth, shape, earth embankment and excavation, inlet and outlet, effluent utilization, water supply, safety, and visual appearance. It also outlines the operation and maintenance procedures, such as start-up, operational depth and loading, salt build-up, crust, sludge removal, and inspection.

Design procedures for aerobic and facultative lagoons are given by USDA-NRCS method (1992). The engineering considerations for construction, operation, and maintenance are similar to anaerobic lagoons.

References

ASAE, 1999. Design of anaerobic lagoons for animal waste management. ASAE EP 403.3. ASAE Standards 1999. American Society of Agricultural Engineers. 2950 Niles Road, St. Joseph, MI.