2. BIOLOGICAL NITRIFICATION AND DENITRIFICATION

2.1 Introduction

This chapter aims to give a broad overview of the biological nitrification and denitrification systems and to compare the different unit processes explained in detail in later chapters. This should facilitate the understanding of the following chapters 3-6, dealing with the biological unit processes.

The contents of this chapter may be summarized as follows:

1) Classification of the different nitrification and denitrification unit processes (section 2.2).

2) The terminology used in the basic waste water treatment (section 2.3).

3) Comparison of the biofilm (attached-growth) and the activated sludge (suspended-growth) unit processes (section 2.4).

4) Comparison of the nitrification rate for the unit processes described in later chapters (section 2.5).

The removal of nitrogen by biological nitrification and denitrification is a two-step process. In the first step (nitrification) ammonia is converted aerobically to nitrate (NO_3^-). In the second step (denitrification) nitrates are converted to N_2O or nitrogen gas (N_2) under anoxic conditions.

Nitrification is an autotrophic process which means that the energy for bacterial growth is derived from the oxidation of nitrogen compounds, primarily ammonia. In contrast to heterotrophs, nitrifiers use carbon dioxide as a carbon source rather than organic carbon for the synthesis of new cells. Nitrifier cell-yield per unit of substrate metabolized is many times smaller than the cell yield for heterotrophs and denitrifier, see Table 2.3.

As will be described in Chapter 3 the nitrification process is a two-step process involving two genera of microorganisms, *Nitrosomonas* and *Nitrobacter*. In the first step, ammonium is converted to nitrite; in the second step, nitrite is converted to nitrate. The conversion processes are outlined in Section 3.4.

Chapter 4 describes how the denitrification can be accomplished biologically under anoxic conditions. Two types of enzyme systems are involved in the reduction of nitrate: assimilatory and dissimilatory. In the assimilatory nitrate reduction process, NO_3^- -N is converted to ammonia nitrogen for the use by the cells in biosynthesis. It occurs when NO_3^- -N is the only form of nitrogen available. In the dissimilatory nitrate reduction process, nitrogen gas is formed from nitrate. This latter process is normally called denitrification of waste water, and demands a carbon source to provide energy for the process. More than 2000 species of bacteria can perform the dissimilatory denitrification process.

2.2 Classification of Nitrification and Denitrification Unit Processes

The nitrification and denitrification unit processes can be divided into two broad classes, the attached growth systems, and the suspended growth systems.

In the attached-growth (biofilm) process (Chapter 5), the bulk of the biomass is retained on a medium and it does, therefore, not require a solids separation step for returning the solids to the nitrification reactor. The media that carry the nitrifying biofilm can be anything from plastic media to Nitrogen ion-selective zeolites. Trickling towers, Rotating Biological Contactors (RBC), Upflow Fixed Bed Reactors (UFBR) are the most widely used for biofilm systems.

Suspended-growth (activated sludge) processes (Chapter 6) take place on suspension of the biological solids in a mixed liquid. The result is the activated sludge processes, based on only nitrifying bacteria, or on a combination of oxidative and nitrifying bacteria, depending on the influent waste water. A subsequent clarification stage is required to return the microorganisms to the nitrification stage.

The activated sludge and the biofilm systems can be further subdivided into systems which use different variations of combined oxidation-nitrification processes and separate stages of nitrification or denitrification processes. Table 2.1 gives an overview of the different applications.

Further details of the different biological unit operations for the removal of nitrogen are outlined in Chapter 5 for the attached-growth systems and in Chapter 6 for the activated sludge processes.

The demarcation between the biofilm and the activated sludge processes is not always very clear. For example in the fluidized bed, the medium consists of solid particles covered with a biofilm, and moves in the reactor. This principle is, therefore, similar in some ways to the activated sludge process.

Table 2.1 Classification of different combined nitrification/denitrification and separate stage nitrification or denitrification units.

Combined carbon oxidation and nitrification processes (secondary treatment).

Suspended growth processes (activated sludge processes).

Activated sludge system.
Single stage
Two-stage

Attached growth processes (Biofilter processes).

Trickling filters, with different filling material.

Rotating Biological Contractors.

Upflow Fixed Bed Reactor (UFBR), applying different media.

Combination of Biofilter and activated sludge process in two stages.

Combined nitrification and denitrification process.

Suspended growth processes.

Activated sludge systems with alternated oxic conditions.

Attached growth processes (biofilter processes).

Simultaneous nitrification and denitrification applying N-ionselective media in an upflow Fixed Bed Reactor (UFBR).

Separate stage nitrification processes (tertiary treatment).

Suspended growth processes.

Activated sludge processes.

Attached growth processes (Biofilter processes).

Trickling filter.

Rotating Biological Contactor (RBC)

Upflow Fixed Bed Reactor (UFBR).

Fluidized Bed Reactor.

2.3 Terminology Used in Waste Water Treatment.

The terminology used in the treatment of waste water is often confusing. Terms such as primary, secondary and tertiary treatment, in the treatment of municipal waste water, frequently appear in the literature, and their usage is not always consistent.

The meanings of these terms, as used in Chapters 5 and 6 are therefore outlined in this section. Figure 2.1 shows a flow diagram of a typical sewage treatment plant, and indicates the different nitrogen removal steps.

The latter part of this section will show at which step the removal of the nitrogen compounds in the waste water takes place.

Primary treatment:

Primary treatment removes solid material from the incoming waste water. Large particles are removed by screens or reduced in size by grinding devices. Inorganic solids are removed in grit channels and much of the organic suspended solids is removed by sedimentation.

A typical primary treatment system is shown in Fig. 2.2. The primary treatment system will remove almost one-half of the suspended solids in the incoming waste water.

The waste water transported to secondary treatment is called the primary effluent.

Secondary treatment.

Secondary treatment usually consists of a biological conversion of dissolved and colloidal organic compounds into biomass, and its respiration. Some nutrient removal takes place in secondary treatment units, depending on the ratio of heterotrophs and nitrifier in the different unit processes. The different unit processes during secondary treatment are the so-called combined carbon oxidation and nitrification processes. Fig. 2.3 shows the secondary treatment process.

Secondary systems normally produce an excess biomass that is sometimes recycled into the secondary treatment with the influent.

Primary and secondary treatment can sometimes be accomplished simultaneously in an oxidation pond or an aerated lagoon, as shown in Fig. 2.4.

In an oxidation pond, the oxygen is supplied from natural sources, and the oxygen concentration, is therefore low, that is why oxygen rarely penetrates to the bottom of the pond, and the solids that settle are decomposed anaerobically. In aerated lagoon systems, oxygen is supplied by mechanical aeration, and the lagoon is, therefore, aerobic.

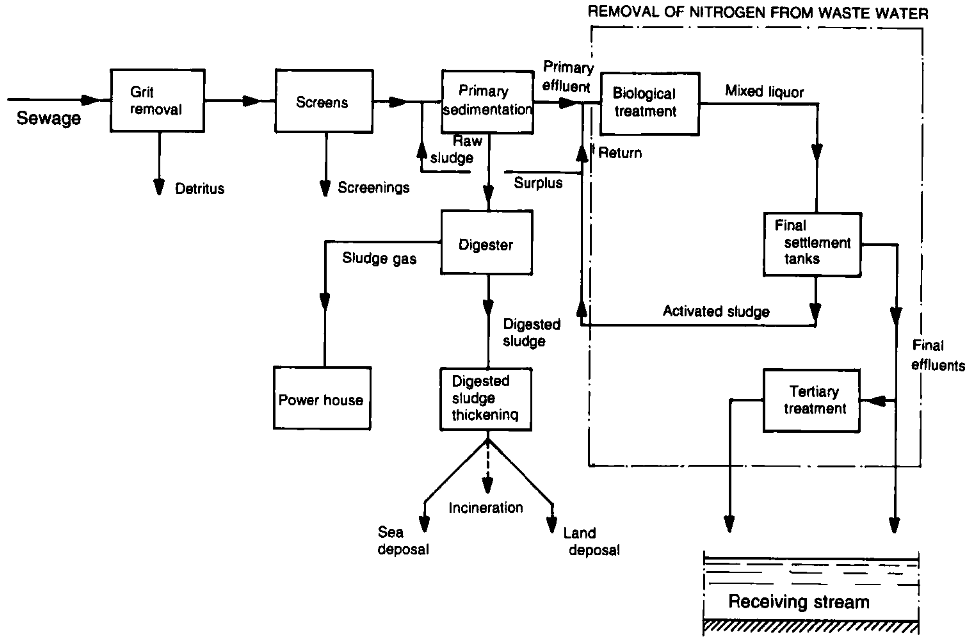

Figure 2.1 Flow diagram of a typical sewage treatment plant.

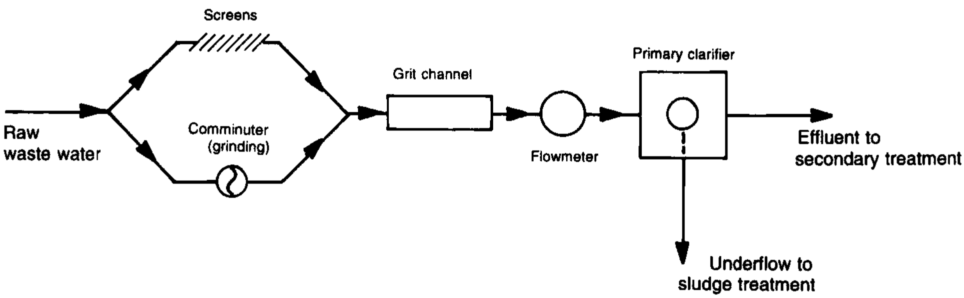

Figure 2.2 Plan of a primary treatment process.

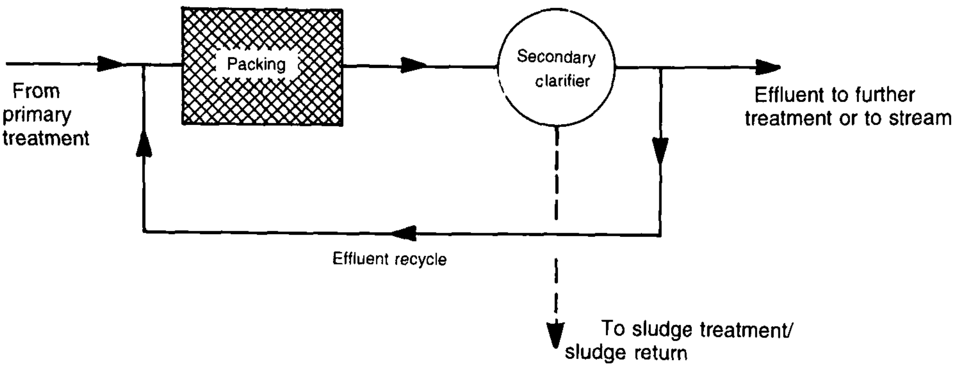

Figure 2.3 Plan of a secondary treatment process.

Tertiary treatment.

The reliability of stable processes has become increasingly important in order to meet today's effluent standards for the nitrogen content in a waste water. It is, therefore, often necessary to introduce another treatment step to refine the waste water. Tertiary nitrifying or denitrifying steps are normally the same processes as described under secondary treatment; but the concentration of a nitrifying or denitrifying biomass is much higher, because the influent of organic compounds into a tertiary nitrifying treatment is so low, that it will not cause a competition between the heterotrophic and nitrifying bacteria, and thus lowers the nitrification rate. Tertiary nitrifying unit processes have, therefore, a higher nitrification rate than the combined oxidation and nitrification steps.

2.4 Comparison of the Biofilm and Activated Sludge Unit Processes

Biofilm techniques are generally used in small sewage works, serving populations of less than 20 000. They tend to be higher in capital costs but lower in running costs than activated sludge plants.

Biofilms oxidize generally more nitrogen than activated sludge per unit of bed volume, but the final effluent carries more suspended solids. Activated sludge processes usually require more skilled operators and more frequent maintenance than biofilms, and activated sludge processes are often difficult to apply, particularly in small communities.

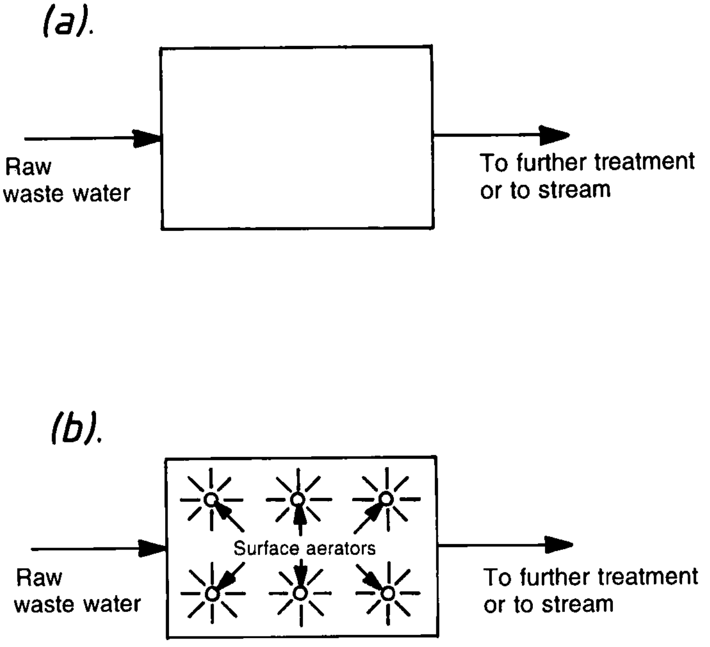

Figure 2.4 Oxidation pond and aerated lagoon with simultaneous primary and secondary treatment

Several experiments have been made to combine the suspended and attached growth systems as listed in Table 2.2.

The main reasons for the combined cultivation are as follows:

- increase in reactor capacity
- increase in the biomass content in the system without an additional loading of the unit process
- achievement of better and more stable nitrification.

Table 2.3 shows a comparison of the amount of suspended solids produced and the yield coefficient in different nitrifying and denitrifying unit processes. Data for the organic compounds are added to the list for comparison. Nitrifiers, both in suspended and attached growth systems have a low yield coefficient and a low sludge production. Denitrifers have a low sludge production, but much higher yield coefficient. The nitrification process would, therefore, appear to be very difficult to initiate, compared with the denitrification process. As a comparison the heterotrophic bacteria have a high yield coefficient and ten times greater sludge production than the nitrifier.

Table 2.2 Examples of combination of suspended and attached growth processes for the nitrifying units described in the literature.

Example	References
Plastic foam particles freely dispersed in the suspended culture of activated sludge.	Hegemann (1983) Rogella and Payraudeau (1987) Rogella and Jarosz (1987)
Blocks of Trickling Filter packing materials submerged in activated sludge tanks.	Lang (1981) Rogella and Jarosz (1987) Rogella *et al.* (1988) Schlegel (1988)
Rotating Biological Contactor (RBC) partly submerged into activated sludge (SURFACT process).	Guarino *et al.* (1980)
Packed-Cage RBC	Wanner *et al.* (1990)

2.5 Comparison of the Nitrification Rate for Different Unit Processes.

In Table 2.4 a comparison is made between the different nitrification rates as a function of the temperature, from data found in the literature. The results shown are presented either with the surface rate in g N/ m^2 * day or the media volume rate in kg N/ m^3 • day.

Results show that the submerged filters generally has high nitrification rates; in particular the submerged filter named *biocarbone*, developed by OTV in France, is among the unit processes with the highest nitrification rate. Generally the biofilm unit processes appear to have a higher nitrification rate than the activated sludge processes, expressed with the above indicated units.

Table 2.3 Comparison of the developed amount of suspended solids and yield coefficients in the different nitrifying and denitrifying unit processes. For comparison, data for heterotrophs are added to the list.

Process	*Yield coefficient volatile suspended solids (VSS)*	*Sludge Production g VSS / m^3 sewage*
Activated sludge with nitrification	0.6 g VSS / g BOD	120
Trickling filter	0.4 g VSS / g BOD	80
Separate stage nitrification	0.1 g VSS / g NH_4^+ - N	2
Comb. suspended nit/denit	0.5 g VSS / g BOD	100
Separate stage denitrification with suspended unit	0.8 g VSS / g NO_3^- - N	16
Separate stage denitrification with biofilter unit	0.6 g VSS / g NO_3^- - N	12

From: EPA (1975)

Table 2.4 A comparison of the peak nitrification rate for various units, both attached and suspended growth processes, at different temperatures, a).

Reactor type	Volumetric nitrification rates (kg N/m^3 · d) at various temperatures °C The RBC reactor is indicated as kg N/m^2 · d (superficial nitrification rate) and results indicated in brackets.					
	10°	15°	20°	22°	25°	Reference
Simultaneous nitrification and denitrification pilot plant **b)**				3,6		Halling-Sørensen and Hjuler (1993)
Biofilm-Controlled Nitrifying Trickling Filter (BCNTF)	0,36	0,32	0,40			Parker *et al.* (1989)
RBC	(1,7-2,1)					Gujer and Boller (1989)
RBC					(3,6)	Antonie (1974)
Biocarbone (BAF and I. Krüger)				>0,75		Rogella and Payraudeau (1987)
Linpor (foam cubes in suspension)				0,32		Rogella and Payraudeau (1987)
Packed bed reactor gravel (5 mm gravel)			0,21	0,24	0,32	Gasser *et al.* (1974)
Fluidized bed reactor High porosity medium, activated carbon			0,48			Metcalf and Eddy (1991)
Activated sludge	0,12	0,19	0,28 0,40	0,32 0,50	0,38 0,60	Wild *et al.* (1971) Stamberg *et al.* (1974)

Partly from Parker *et al.* (1990)

a) Data are reported for comparative purposes only. If any of these processes are to be applied, pilot plant testing is recommended to verify removal rates.

b) Only reactor type that can perform simultaneous nitrification and denitrification.

2.6 Conclusions

The following conclusions can be made on the basis of a comparison between the nitrifying attached and suspended growth processes.

1. The nitrification rate for the attached-growth processes is higher than for the suspended-growth processes.

2. The attached-growth processes are generally used in small sewage works (less than 20 000 Person Equivalent (P.E.)), while the suspended-growth processes are used in large treatment works. Today much effort is being put into the development of large attached-growth sewage works. The future will, therefore, without any doubt show more and more use of the biofilm technology for even larger treatment plants.

3. Attached-growth processes normally carry more suspended solids in the effluent than the suspended-growth processes.

4. Activated sludge processes usually require more skilled operators and more frequent mainteinance than the attached-growth process.