order of 0.2 g COD/g cells · day. Certain metal ions (Na^+, K^+, Ca^{2+}, Mg^{2+}) are known to be toxic to organisms of anaerobic digesters at high concentrations (> 1000 mg/l), although they are stimulatory at low levels (< 100 mg/l).

The composition of the product gas mixture varies, depending on the composition of waste material and other environmental factors. A typical gas composition is 70% to 75% CH_4, 20% to 25% CO_2, and 5% H_2S and other gases (NO_2, H_2, CO). Part of the methane produced in an anaerobic digestion unit is used to heat the digesters to fermentation temperature. The digester gas has a heating value of 24 to 28 million J/m^3, and the yield is 0.75 to 1.2 m^3 (std)/kg of organic material decomposed, resulting in an energy generation of 18 to 33 million J/kg of organic material. One problem associated with the use of digester gas is the H_2S content, which can cause foul odors and corrosion and needs to be removed before use.

Anaerobic digesters were originally designed as closed stationary tanks. In newer designs, reactor contents are mixed and the reactor is heated. Mixing is accomplished either by recycling a portion of the gas or by mechanical stirring. The reaction mixture is highly heterogeneous and viscous and, therefore, difficult to mix. Figure 16.10 is a schematic diagram of an anaerobic digester. Anaerobic digestion can be achieved in packed beds containing porous solid support particles. Bacteria grow on support surfaces and inside pores, and liquid waste may be trickled through the bed. Solids recycling schemes have been developed for use with conventional digesters that simulate activated-sludge units. Solids residence times are considerably higher than hydraulic residence times in these systems, which results in biomass accumulation and higher reaction rates. Continuous plug flow reactors operated in upflow mode are commonly used as anaerobic digesters.

The solids content of sludge (waste) is reduced by about 50% to 60% at the end of anaerobic digestion. Digested sludge is much less biodegradable than raw sludge and is easier to dewater. The digester effluent is dewatered by vacuum filtration and is dried. The dried solids are either incinerated or spread on land as fertilizer.

16.6.3. Advanced Waste-water Treatment Systems

Advanced waste-water treatment systems are used for removal of residual nitrogen and phosphorus along with refractory carbonaceous compounds. Examples are for nitrification and denitrification, phosphate removal processes (e.g., PhoStrip and A/O processes), and combined nitrogen and phosphate removal processes (e.g., A^2O and Bardenpho processes).

Nitrogen-containing organic compounds (e.g., amino acids and proteins) are oxidized biologically to ammonium, which is further oxidized to nitrite and nitrate by *Nitrosomonas* and *Nitrobacter,* respectively. The conversion of ammonium to nitrate by microbial catalysis is called *nitrification.*

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{Nitrosomonas} NO_2^- + H_2O + 2H^+ \qquad (16.50a)$$