However, many media contain proteins as substrates, which limits the usefulness of this approach.

The intracellular ATP concentration (mg ATP/mg cells) is approximately constant for a given organism. Thus, the ATP concentration in a fermentation broth can be used as a measure of biomass concentration. The method is based on luciferase activity, which catalyzes oxidation of luciferin at the expense of oxygen and ATP with the emission of light.

$$\text{luciferin} + O_2 + \text{ATP} \xrightarrow{\text{luciferase}} \text{light} \tag{6.4}$$

When oxygen and luciferin are in excess, total light emission is proportional to total ATP present in the sample. Photometers can be used to detect emitted light. Small concentrations of biomass can be measured by this method, since very low concentrations of ATP (10^{-12} g ATP/l) can be measured by photometers or scintillation counters. The ATP content of a typical bacterial cell is 1 mg ATP/g dry-weight cell, approximately.

Sometimes, nutrients used for cellular mass production can be measured to follow microbial growth. Nutrients used for product formation are not suitable for this purpose. Nitrate, phosphate, or sulfate measurements can be used. The utilization of a carbon source or oxygen uptake rate can be measured to monitor cellular growth when cell mass is the major product.

The products of cell metabolism can be used to monitor and quantify cellular growth. Certain products produced under anaerobic conditions, such as ethanol and lactic acid, can be related nearly stoichiometrically to microbial growth. Products must be either growth associated (ethanol) or mixed growth associated (lactic acid) to be correlated with microbial growth. For aerobic fermentations, CO_2 is a common product and can be related to microbial growth. In some cases, changes in the pH or acid–base addition to control pH can be used to monitor nutrient uptake and microbial growth. For example, the utilization of ammonium results in the release of hydrogen ions (H^+) and therefore a drop in pH. The amount of base added to neutralize the H^+ released is proportional to ammonium uptake and growth. Similarly, when nitrate is used as the nitrogen source, hydrogen ions are removed from the medium, resulting in an increase in pH. In this case, the amount of acid added is proportional to nitrate uptake and therefore to microbial growth.

In some fermentation processes, as a result of mycelial growth or extracellular polysaccharide formation, the viscosity of the fermentation broth increases during the course of fermentation. If the substrate is a biodegradable polymer, such as starch or cellulose, then the viscosity of the broth decreases with time as biohydrolysis continues. Changes in the viscosity of the fermentation broth can be correlated with the extent of microbial growth. Although polymeric broths are usually non-Newtonian, the apparent viscosity measured at a fixed rate can be used to estimate cell or product concentration.

6.2.2. Growth Patterns and Kinetics in Batch Culture

When a liquid nutrient medium is inoculated with a seed culture, the organisms selectively take up dissolved nutrients from the medium and convert them into biomass. A typical batch growth curve includes the following phases: (1) lag phase, (2) logarithmic or exponential growth phase, (3) deceleration phase, (4) stationary phase, and (5) death phase. Figure 6.3 describes a batch growth cycle.