9.5. SOLID-STATE FERMENTATIONS

Solid-state fermentations (SSF) are fermentations of solid substrates at low moisture levels or water activities. The water content of a typical submerged fermentation is more than 95%. The water content of a solid mash in SSF often varies between 40% and 80%. Solid-state fermentations are usually used for the fermentation of agricultural products or foods, such as rice, wheat, barley, corn, and soybeans. The unique characteristic of solid-state fermentations is operation at low moisture levels, which provides a selective environment for the growth of mycelial organisms, such as molds. In fact, most solid-state fermentations are mold fermentations producing extracellular enzymes on moist agricultural substrates. Since bacteria and yeasts cannot tolerate low moisture levels (water activities), the chances of contamination of fermentation media by bacteria or yeast are greatly reduced in SSF. Although most SSFs are mold fermentations, SSFs based on bacteria and yeast operating at relatively high moisture levels (75% to 90%) are also used. Solid-state fermentations are used widely in Asia for food products, such as tempeh, miso, or soy sauce fermentations, and also for enzyme production.

The major advantages of SSFs over submerged fermentation systems are (1) the small volume of fermentation mash or reactor volume, resulting in lower capital and operating costs, (2) a lower chance of contamination due to low moisture levels, (3) easy product separation, (4) energy efficiency, and (5) the allowing of the development of fully differentiated structures, which is critical in some cases to product formation. The major disadvantage of SSFs is the heterogeneous nature of the media due to poor mixing characteristics, which results in control problems (pH, DO, temperature) within the fermentation mash. To eliminate these control problems, fermentation media are usually mixed either continuously or intermittently. For large fermentation mash volumes, the concentration gradients may not be eliminated at low agitation speeds, and mycelial cells may be damaged at high agitation speeds. Usually, a rotating-drum fermenter is used for SSF systems, and the rotational speed needs to be optimized for the best performance.

Solid-substrate fermentations imply a more general method of fermentations in which moisture content may not need to be low, but the substrate is in the form of submerged solid particles in liquid media. Bacterial ore leaching (i.e., growth and microbial oxidation on surfaces of mineral sulfide particles) or fermentation of rice in a packed column with circulating liquid media are examples of solid-substrate fermentations. Solid-state (or solid-phase) fermentations are a special form of solid-substrate fermentations for which the substrate is solid and the moisture level is low.

The *koji process* is an SSF system that employs molds (*Aspergillus, Rhizopus*) growing on grains or foods (wheat, rice, soybean). A typical SSF process involves two stages. The first and the primary stage is an aerobic, fungal, solid-state fermentation of grains called the *koji*. The second stage is an anaerobic submerged fermentation with a mixed bacterial culture called the *moromi*. The products listed in Table 9.3 are the products of aerobic SSF, the koji process. Fermentation in the second stage (moromi) may be realized by using the natural flora, or, usually, with externally added bacteria and yeasts. Some strains of *Saccharomyces*, *Torulopsis*, and *Pediococcus* are used as flavor producers in soy sauce manufacture. The moromi is usually fermented for 8 to 12 months. However, the processing time can be reduced to 6 months by temperature profiling. The final product is pressed to recover the liquid soy sauce and is pasteurized, filtered, and bottled.