Colony Shapes of Microorganisms

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1. Introduction

People are affected by fungal growth in the food stock or bathroom, particularly in humid conditions. In addition, fungi can degrade even petroleum (Lemos *et al.*, 2002), coexist with humans, and grow well in artificial environments. However complete eradication of fungi would seriously affect the Earth's carbon cycle as it can decompose large amounts of nutrient-poor leaves that accumulate on the ground, releasing carbon dioxide into the atmosphere through respiration, which is necessary for plant photosynthesis.

2. Colony Shapes and Environmental Condition

Fungal hyphae (parts like thread) produce multi-branched filaments with diameters of 230 μm. The networks of hyphal filaments constitute the fungal mycelium. Along the axis of filaments, there are four different zones. Hyphae extend at their apical growth zone, which is followed by the absorption zone, which is responsible for nutrient uptake. The third zone is the nutrient storage zone, and the oldest zone is called the senescence zone, which is where cell lysis (decay of cell) takes place (Jennings and Lysek, 1996).

Hyphae penetrate into the soil or into animal and plant cells, and secrete digestive enzymes that decompose nutrient substances. They absorb decomposed nutrients and secrete waste products. The accumulation of waste products and overcrowding of hyphae exerts inhibitory effects on hyphal growth.

Fungal mycelia grow and form macroscopic colonies. There are two types of hyphae: the basal hypha that penetrates into the substrate to absorb nutrients and aerial hypha that extends into the air for efficient respiration and also explores new substrates.

Fungal colonies change their shapes and growth rates according to the environmental conditions. The author performed cultivation experiments of several strains of *Aspergillus* species on a solid agar medium containing various glucose and agar concentrations (Matsuura, 2002). *Aspergillus oryzae* is particularly familiar in Japan because it is used to produce foods and ingredients consumed daily, such as miso (fermented soybean paste), soy source, sake, and dried bonito.

Fibers of agar function as the skeleton of the substrate, retaining water molecules inside the substrate. As the concentration of the agar decreases, the softness and fluidity of the substrate increases, resulting in faster diffusion of the nutrient substance into the substrate. Although the hyphae absorb nutrients from the surrounding space, the remaining nutrients continuously diffuse into the colonized space.

Conversely, mycelia generally form colonies on the surface of the substrate, which is preferable for sufficient respiration. The growth rate of mycelia decreases when they are submerged into liquid.

3. Ramified Colony

Figure 1 shows the pictures of *Aspergillus* colonies grown on agar. These colonies were grown from spores inoculated in line. Fungal colonies exhibited various shapes depending upon concentrations of glucose and agar (Matsuura, 1998).

Particularly, ramified colonies (colonies with branches) were formed on an extremely soft medium containing a low nutrient concentration. The colony shapes resembled an array of branched trees. Such a ramified shape is found in the diffusion-limited aggregation of non-living materials, such as electro-depositions.

In diffusion-limited aggregation, the diffusing particles approach the aggregate in a random motion, and they occasionally attach to the aggregate on contact. Many particles are absorbed into the apical area of the aggregate, and few particles reach the inner area of the aggregate. Thus, diffusion-limited aggregates exhibit a branched shape with many voids left in their inner spaces. These aggregates are called diffusion-limited aggregates because their growth rate is limited by the diffusion of particles.

Taking the growth of branched fungal colonies based on the mechanism of diffusion-limited aggregation into consideration, hyphal growth is reduced in a medium with high fluidity, and consequently, the medium inside the colonized area deteriorates. Therefore, older hyphae inside the colony have a less chance of extending further. Younger hyphae in the apical region of the branched colony extend by absorbing nutrients diffusing from outside the colony.

A simple computer model of colony patterning was created to represent these growth phenomena (Matsuura,

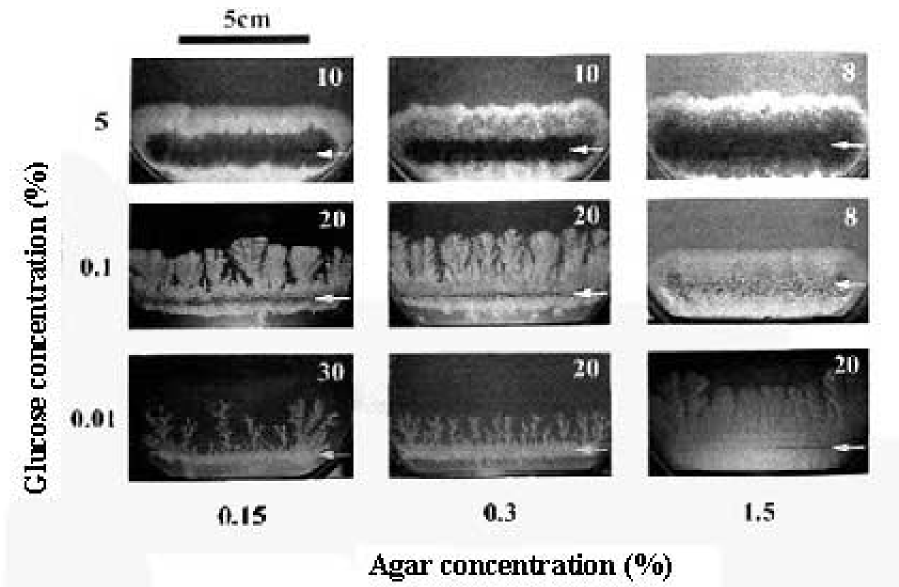

Fig. 1. Colonies of *Aspergillus oryzae* grown on the surface of a synthetic agar medium. The shapes of the fungal colonies changed in response to different nutrient and agar concentrations in the medium. In the figure, the glucose concentration was increased from 0.01% to 5% vertically, and the agar concentration was increased from 0.15% to 1.5% horizontally. At an agar concentration of 0.15%, the medium is nearly fluid. Numbers in the pictures indicate the days of cultivation after spore inoculation. Arrows denote the lines of spore inoculation. The white portions are the aggregates of hyphae, and the black materials are spores produced on the hyphae.

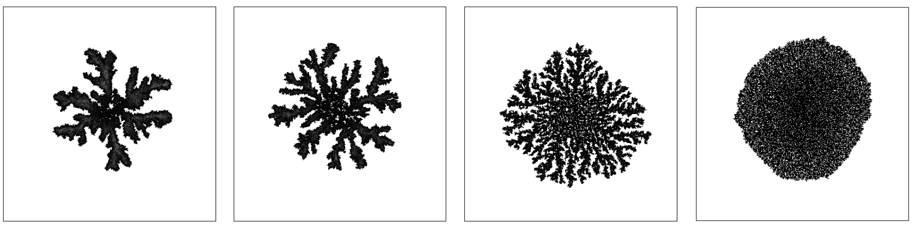

Fig. 2. Computer model of colonies created at a low nutrient concentration with various nutrient diffusion effects. The diffusion effect was reduced at a constant nutrient uptake frequency of $G = 0.1$. From left to right, $R_s = 100$, 50, 10, and 1, respectively. Initially, four nutrient particles were stored at each lattice point ($N_i = 4$). Squares show the region of a 400×400 square lattice.

2002). The model colonies were developed on a two-dimensional square lattice, of which the lattice points initially possess a specified number of nutrient particles. The amount of total nutrient particles stored in the lattice points is one primary parameter. The nutrient particles are individually released to walk at random on the square lattice for a given number of steps. The length of the random walk trajectory R_s is the parameter of nutrient diffusion. The third primary parameter G is the frequency of nutrient uptake, and it is proportional to the hyphal production rate. When random nutrient walk occurs n times before the uptake of one nutrient particle, G is equal to $1/n$. Finally, when the number of nutrient particles stored within a hyphal unit cell reaches a certain amount, the hyphal cell creates a daughter cell at a randomly chosen unoccupied neighboring lattice site that consumes n_r stored nutrients. One parent hyphal cell creates up to two daughter cells, and the parent cell retains nutrients absorbed after the production of the two daughter cells.

When the total amount of nutrients N_i was small, the colony patterning changed with the diffusion effects as shown in Fig. 2. First, when the nutrient diffusion effect was high, i.e., with the combination of high R_s and low G, the colony exhibited ramified shapes similar to those observed during diffusion-limited aggregation. The colonies had large voids in their inner spaces and condensed hyphal production.

Second, upon decreasing the diffusion effect, i.e., as R_s was lowered, the hyphal system covered the medium homogeneously, and a circular colony with low hyphal density was found.

Computer model simulations suggest that the overall tendency of colony patterning could be explained by the physical conditions such as the nutrient concentration, diffusion, and hyphal growth rate.

Fungal colonies regulate the survival of mycelia. Colonies attach to the substrate in various conditions and interact with other microorganisms by secreting chemical substances. The secreted substances can serve as chemical signals or induce adverse effects in the other microorganisms. In addition, the colonies store nutrients and protect the fungi against adverse environmental conditions such as dryness. Explorative hyphae extend rapidly to locate a new nutritional substrate using nutrients stored inside the colony.

4. Concluding Remarks

Fungal colonies grow according to the physical and biological environmental conditions. At the same time, they demonstrate strategies of survival, adapting to the conditions with minimal energy consumption. Their strategies in response to environmental conditions are expressed in the shapes of colonies. The life form of filamentous fungi is indeed sufficiently flexible and efficient to explore and exploit inhomogeneous, patchy environments.

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