MYCOLOGY ANSWERS

IRON IS RELATIVELY INSOLUBLE AND OFTEN UNAVAILABLE IN THE NATURAL ENVIRONMENT: HOW DO FUNGI OBTAIN SUFFICIENT SUPPLIES?

Iron is important for the growth and continued vitality of living organisms. It is usually regarded as a trace mineral but is required in comparatively large amounts. Without supplies of iron cells suffer from metabolic stress and growth patterns are quickly disrupted. Iron is a key component of essential proteins, particularly those involved in cellular respiration (cytochromes), and iron-sulphur proteins are involved in electron transport and energy conservation in cells. It is also an important component of some pigments.

The availability of iron in the natural environment is generally low. It is also relatively insoluble and as a consequence it is not easily assimilated by living organisms. Ferric iron (Fe^{3+}) is the most common form to be found in soils and rocks. However, the ferrous form (Fe^{2+}) is more soluble and therefore more available to microbes. The reduction of ferric to ferrous iron can be brought about by bacteria in the natural environment, which makes it more readily available to other organisms. This microbial action forms an important process in the geochemical cycling of iron. The pH of the environment is important to the solubility and therefore the availability of iron to fungi. More iron is present in solution in acid soils but it is more insoluble in neutral or alkaline situations. At neutral pH the only way that iron is maintained in solution is by chelation with organic materials. Indeed, providing sufficient iron in culture media can be a problem owing to this low solubility. In laboratory cultures chelating agents can be added in order to complex the iron and make it more available.

Fungi have evolved special mechanisms for the selective uptake of iron. Some produce organic acids which chelate iron and in general, as fungi grow the surrounding medium becomes acidified which may help to maintain the amount of available ferric ions but is probably insufficient to allow iron transport into cells. During times of iron limitation many fungi produce siderophore molecules which act specifically to solubilise it and effect transport into the cells helping to overcome iron stress in fungi. The synthesis of siderophores which are low molecular weight (500-1000D) ferric-specific ligands is linked to, and regulated by, the availability of iron in the immediate environment. Once inside the cells, iron is bound to siderophores or polyphosphates for storage and later use. In most cases siderophores are synthesised only during iron limitation and not continuously during growth. It is interesting that even in species that do not synthesise siderophores these molecules can be used as a source of nutrients and appear to have a growth stimulating effect. Indeed, some fungi may gain competitive advantage in the natural environment from their ability to use siderophores produced by other species.

A range of siderophore molecules with differing molecular structures have been described within the fungi, although many are similar in structure and function to those found in bacteria. The majority of fungal genera synthesise hydroxamate-type siderophores, particularly ascomycetes and basidiomycetes. Four classes of hydroxamate siderophores have now been distinguished, all of which contain ornithine as the iron binding residue. The ferrichromes complex with ferric iron and have been found in *Ustilago sphaerogena*, as well as species of *Aspergillus*, *Trichoderma*, *Penicillium* and others. The fusarinines are widely found among some groups of fungi (e.g. in species of *Fusarium*, *Gliocladium*, *Penicillium*). Coprogens (found in some *Penicillium* strains, *Neurospora crassa*, *Histoplasma capsulatum*) and rhodotorulic acid (found in *Rhodotorula*, *Sporobolomyces* and others) have also been described. In addition, novel complexone-type siderophores (ferritins) have recently been reported to occur in the zygomycetes (*Rhizopus microsporus* var *rhizopodiformis*, *Mucor mucedo*, *Cunninghamella elegans* and others).

There have been reports of several mechanisms by which siderophores and iron are transported into fungal cells. The reductive removal of iron may occur inside or outside the cell membrane depending on the kind of siderophore molecules involved. Intact iron chelate (siderophore) molecules may be actively transported into cells, requiring the use of metabolic energy, across the plasma membrane. It is probable that iron is then released to metabolic processing by the reduction or degradation of siderophore molecule. In this way the iron is delivered directly to membrane located iron-acceptors. Alternatively, the siderophore may chelate and transport iron to the outside of the plasma membrane from where the iron is released and transported across the membrane via a permease. Fungi which do not depend on siderophores (e.g. *Saccharomyces cerevisiae*, some species of *Geotrichum* and *Candida*) have iron-specific ferric reductase and transport ferrous iron across the cell membrane.

There is also evidence that some siderophores may have a role in iron storage, particularly in fungal spores (e.g. ferricrocin in conidia of *Neurospora crassa*). It may be that in some species several types of siderophores are synthesised; some for iron capture from the environment and others for iron storage. Some siderophores may be specifically contained within cells (intracellular siderophores) whereas others are secreted to the environment (extracellular siderophores). In instances where potential iron storage siderophores are contained in fungal spores these molecules are likely to have an important role in regulating the onset and progress of sporulation and spore germination.

It is clear therefore that siderophores have a vital role in the regulation of the capture, transport and storage of metabolisable iron in fungal cells and therefore also in their growth and development.

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