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Research review paper

Mucor indicus: Biology and industrial application perspectives: A review

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ABSTRACT

Mucor indicus, one of the most important strains of zygomycetes fungi, has been the subject of several studies since a couple of hundred years ago. This fungus, regarded as a non-pathogenic dimorphic microorganism, is used for production of several beers and foods. Morphology of the fungus can be manipulated and well controlled by changing a number of parameters. Furthermore, *M. indicus* can grow on a variety of substrates including lignocellulosic hydrolysates which are mixtures of hexoses, pentoses, and different severe fermentation inhibitors. Indeed, high yield ethanol production is among the most important features of this strain. Presence of considerable amounts of chitosan in the cell wall is another important aspect of the fungus. Besides production of ethanol and chitosan, the biomass of this fungus has shown a great potential to be used as a rich nutritional source, e.g. fish feed. The fungus is also among the oleaginous fungi and produces high amounts of polyunsaturated fatty acids particularly γ-linolenic acid. Furthermore, the biomass autolysate has a high potential for yeast extract replacement in fermentation by the fungus. Additionally, the strain has shown promising results in heavy metal removal from wastewaters. This review discusses different aspects of biology and industrial application perspectives of *M. indicus*. Furthermore, open areas for the future basic and applied levels of research are also presented.

Contents

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1. Introduction

Having about 1.5 million species, fungi have the second highest number of species after insects (Feofilova, 2001). By development of biotechnology, fungi have got a crucial importance in production of a wide range of products such as different foods, biofuels, enzymes, antibiotics, and chemicals. Zygomycota is the most varied and least studied phylum of fungi that is divided into two subphyla, trichomycetes and zygomycetes. Being a source of human food for several hundred years together with promising performance in production of different products in the current decades has put zygomycetes at the center of a large number of recent research activities (Zamani et al., 2010). Among different zygomycetes, *Mucor* is a genus of about 3000 members that are widely distributed in the soil, digestive systems, plant surfaces, and decomposed vegetables. Indeed, *Mucor indicus* was one of the earliest discovered and most studied species of this genus. Followed by discovery in 1860s, different features of biology including morphology, biosynthesis, and metabolism as well as applications of this fungus have been extensively studied (Bartnicki-Garcia, 1963; Bartnicki-Garcia and Nickerson, 1961, 1962b; Bartnicki-Garcia and Reyes, 1964; Bettinger, 1917, 1920; Gordon et al., 1971; Haidle and Stock, 1966). However, despite the broad and long term studies, several aspects of the fungus especially morphology, cell characteristics, and new applications are still unknown. A new wave of research on *M. indicus* has been initiated since the beginning of the 21st century, when *M. indicus* was introduced as a promising microorganism with several potential industrial importance such as co-production of ethanol and chitosan from lignocellulosic waste materials (Abedinifar et al., 2009; Asachi and Karimi, submitted for publication; Asachi et al., 2011; Heidary et al., 2013; Javanbakht et al., 2011; Jeihanipour et al., 2009; Karimi et al., 2005; Millati, 2005; Millati et al., 2005, 2008; Sues et al., 2005). This review paper discusses the results of more than 150 years of research on *M. indicus* and its scientific and industrial prospects in the future.

2. Taxonomy, pathogenesis, and history of *M. indicus*

In the scientific classification, *M. indicus* is a member of the *Zygomycota* division, Zygomycetes class, *Mucorales* order, *Mucoraceae* family, *Mucor* genus, and *indicus* species. This strain is also known as "*Mucor rouxii*" (Chatterjee et al., 2005; de Almeida et al., 1997; Flores-Martinez et al., 1990; Guthmann et al., 1990; Laoteng et al., 2005, 2008; Lending et al., 1991; Majumdar et al., 2008; Martinez-Pacheco and Ruiz-Herrera, 1993; Mullen et al., 1992; Passorn et al., 1999; Ramirez-Salgado et al., 1996; Sabanero et al., 1995; Salcedo-Hernandez et al., 1994; Wei et al., 2004; Yan, 2001), "*Amylomyces rouxii*" or "*Chlamydomucor rouxii*" (Ellis et al., 1976; Fukushima et al., 2005; Goupil, 1912, 1913; Hung and Chou, 1997; Musarrat et al., 2010; Watanabe and Oda, 2008; Yu and Chou, 2000), and "*Mucor rouxianus* (*Calmette*)" (Aggelis et al., 1988; Chen et al., 1999; Nishigami and Amano, 1970; Schroeder, 1961; Tachibana, 1969; Taga and Sakurai, 1991; Tsuboi et al., 1974; Yamasaki et al., 1977; Zhu et al., 2004) in the literature.

The *Mucorales* are among the *Zygomycota* fungi, whose spores arise by cleavage of the sporangial membrane. Members of *Mucor* species are known as contaminants in some cases but very rarely considered as etiologic agents (Guarro et al., 1999). They are usually not pathogens, although some species cause a type of opportunistic infection referred to as "Mucormycosis". Among different morphologies, the filamentous form of *Mucor* species is usually associated with infected tissues (Emmons et al., 1977).

Recognition of *Mucorale* can be easily done by observing only the macroscopic features, woolly colonies with small dots (sporangia) that appear in a few days and spread over a Petri dish containing rich media (Sharifia, 2007).

For the first time, *Mucor* was recognized in 1665 (Ainsworth, 1965). Dimorphism of *Mucor* was historically interesting for the microbiologist and noticed over a century ago (Berkeley, 1838). At that time, the different morphologies led to flawed interpretations and speculations.

History of research on *Mucor* can be divided into three time periods: before 1860 (Bail, 1857; Berkeley, 1838), between 1860 and 1970 (Bartnicki-Garcia, 1963; Bartnicki-Garcia and Nickerson, 1961, 1962b; Bartnicki-Garcia and Reyes, 1964; Bettinger, 1917, 1920; Gordon et al., 1971; Haidle and Stock, 1966), and after 2005 (Asachi et al., 2011; Karimi et al., 2005, 2006a, 2006b; Lennartsson et al., 2009; Millati, 2005; Millati et al., 2005, 2008; Sharifia et al., 2008; Heidary et al., 2013) (cf. Table 1).

Bail (1857) observed that *Mucor* sp. can grow both as spherical cells multiplied by budding and filamentous forms. He concluded that the cells are *Saccharomyces cerevisiae*, and the fungus is produced during developmental stages of the yeast. This conclusion was then rejected by Pasteur (in 1861), Reess (in 1870), and Fitz (in 1873) (Bartnicki-Garcia, 1963).

Brefeld (1873) cultivated *Mucor* sp. under hydrogen atmosphere and obtained filamentous forms, rather than yeast like form and concluded that the accumulation of produced CO_2 and its acidic properties in the culture was responsible for development of yeast like form. This was rejected by Klebs (1896).

Wehmer (1905) showed that anaerobic condition was the most effective parameter in development of yeast like form in *M. indicus*. He also found that both filamentous and yeast like morphologies produce comparable high amounts of ethanol under both aerobic and anaerobic conditions.

Bartinicki-Garcia and Nickerson in 1960s revealed different aspects of *M. indicus* morphology including the biochemistry of dimorphism as well as effects of atmospheric factors, inoculum size, type and quantity of carbon and nitrogen sources, and addition of various chemicals on the morphogenesis (Bartnicki-Garcia, 1963, 1968a, 1968b; Bartnicki-Garcia and Nickerson, 1962a, 1962b, 1962d, 1961; Bartnicki-Garcia and Reyes, 1968, 1964).

Table 1
History of research on *Mucor*.

Time periods	Main interpretations
Before 1860	*Mucor* is a dimorphic fungus which is the developmental stage product of baker's yeast
1860–1970	*Mucor* is an ethanol producing microorganism whose morphology can be changed and controlled.
After 2005	*Mucor* is a suitable strain for fermentation of lignocellulosic hydrolysates and production of valuable products such as chitosan, fungal extract, oil, and animal feed.