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Thermophilic Fungi: Taxonomy and Biogeography

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A critical reappraisal of taxonomic status of known thermophilic fungi indicating their natural occurrence and methods of isolation and culture was undertaken. Altogether forty-two species of thermophilic fungi *viz*., five belonging to Zygomycetes, twenty-three to Ascomycetes and fourteen to Deuteromycetes (Anamorphic Fungi) are described. The taxa delt with are those most commonly cited in the literature of fundamental and applied work. Latest legal valid names for all the taxa have been used. A key for the identification of thermophilic fungi is given. Data on geographical distribution and habitat for each isolate is also provided. The specimens deposited at IMI bear IMI number/s. The document is a sound footing for future work of indentification and nomenclatural interests. To solve residual problems related to nomenclatural status, further taxonomic work is however needed.

Key Words: Biodiversity, ecology, identification key, taxonomic description, status, thermophile

Introduction

Thermophilic fungi are a small assemblage in eukaryota that have a unique mechanism of growing at elevated temperature extending up to 60 to 62°C. During the last four decades many species of thermophilic fungi sporulating at 45°C have been reported. The species included in this account are only those which are thermophilic in the sense of Cooney and Emerson (1964). Therefore, in dealing with this account we shall adopt Cooney and Emerson's definition of thermophilic fungi as those that have a maximum temperature for growth at or above 50°C and a minimum temperature for growth at or above 20°C. The paper presents a comprehensive systematic account of most of the known species of thermophilic fungi. An attempt to include the natural occurrence and methods of isolation and culture of this unique group of fungi is also given.

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Much is known about the occurrence of thermophilic fungi from various types of soils and in habitats where decomposition of plant material takes place. These include: composts, piles of hays, stored grains, wood chip piles, nesting material of birds and animals, snuff, and municipal refuse, and other accumulations of organic matter wherein the warm, humid, and aerobic environment provides the basic physiological conditions for their development. In these habitats thermophiles may occur either as resting propagules or as active mycelia depending on the availability of nutrients and favourable environmental conditions. Soils in tropical countries do not appear to have a higher population of thermophilic fungi than soils in temperate countries as believed earlier. Their widespread occurrence could well be due to the dissemination of propagules from self-heating masses of organic material (Maheswari *et al*., 1987). Tansey and Brock (1972) observed that the thermophilic fungi are much more common in acid thermal habitats than those of neutral to alkaline pH. Thermophilic fungi constitute a heterogeneous physiological group of various genera in the Zygomycetes, Ascomycetes, Deuteromycetes (Anamorphic Fungi), and Mycelia Sterilia.

The occurrence of thermophilic fungi in aquatic sediment of lakes and rivers as first reported by Tubaki *et al.* (1974), is mysterious in view of the low temperature (6-7^{o}C) and low level of oxygen (average 10 ppm, <1.0 ppm at a depth of 31meters) available at the bottom of the lake. A number of thermophilic fungi survive the stresses such as increased water pressure, absence of oxygen and desiccation (Mahajan *et al*., 1986). Undoubtedly the thermophilic fungi owe their ubiquity and common occurrence in large measure to this special ability to occupy a temperature niche that most other fungi cannot inhabit. More attempts are, however, needed to provide evidence for the active involvement in the substrate from which the thermophilic fungi are being reported. Cooney and Emerson (1964), published the first modern comprehensive account of the taxonomy, biology and activities of thermophilic fungi in which only 13 species were discussed, and several additional thermophilic fungi have been discovered or redefined since then. A subsequent document of thermophilic fungi was published by Mouchacca (1997) in which he attempted a critical reapprisal of the nomenclatural and in some cases also of the taxonomic status of known thermophiles. The present document aims at providing taxonomic and nomenclatural review of the valid taxon by avoiding cases of redundancies by citing synonyms of valid taxon. Latest legal valid names for all the taxa have been used as elaborated by Mouchacca (2000). The original names of some of the taxa have been retained for their taxonimic value.

Isolation, Culture and Taxonomy

Most of the thermophilic fungi grow in simple media containing carbon anf nitrogen sources and a few mineral salts, suggesting that they have very simple nutritional requirements. Simple nitrogen sources like nitrates of sodium and potassium, asparagine and yeast extract support good growth of these fungi (Satanarayana and Johri, 1984)). Thermophilic fungi from different sources/substrates have been isolated by standard isolation procedures. Isolation from the air is made by Petri plate exposure method, from soil and other solid substrates, serial dilution plate method and direct plate method are employed. Theromphilic fungi can be isolated on a variety of standard mycological media. But the following two standard media (Cooney and Emerson, 1964) are the most widely used.

Yeast Starch Agar (Emerson, 1941)

Yeast extract difco powdered	4.0 gm
K_2HPO_4	1.0 gm
$MgSO_4.7H_2O$	0.5 gm
Soluble Starch	15.0 gm
Agar	20.0 gm
Water (1/4 tap, ¾ distilled)	1000.0 ml

Yeast Glucose Agar

Yeast extract difco powdered	5.0 gm
Glucose	10.0 gm
Agar	20.0 gm
Tap water	1000.0 ml

For primary isolations rose bengal (50 mg /L) and streptopenicillin (30 units/ml) are added to the medium. Maintenance of adequate moisture in all cultures at the higher incubation temperature being used was a problem. The elevated temperature resulted in desiccation of the agar in Petri plates. Placing the agar plates in humidified containers having sterilized water solved this problem. The incubation temperature for primary isolation was 45^oC. The container was opened twice daily to aerate the cultures.

Several thermophilic fungi have been isolated during the last four decades but their identification has not been done authentically. Compounding this unfortunate situation is the ecologically important traits such as cardinal temperature for growth and ability to degrade particular substrates differ significantly among species which are culturally and morphologically similar

enough to be confused. The thermophilic fungi mostly belong to Zygomycetes, Ascomycetes and Deuteromycetes (Anamorphic Fungi). No Myxomycetes or Basidiomycetes have been reported as a true thermophile. While collecting information on the taxonomy of thermophilic fungi, we faced difficulties on account of the confusing nomenclature of these fungi. The confusion is due to several reasons: (i) the early taxonomic literature is scattered and is often in languages other than English. (ii) some species have been described repeatedly under different names. (iii) the practice of interchangeably using the names of the sexual (teleomorph) and the asexual (anamorph) stages of the same fungus and (iv) there are instances in the literature of misidentifications of thermophilic fungi

The terminology used for conidia and conidiophores of anamorphic Fungi (Deuteromycetes) in this paper are mainly those recommended by the proceedings of the Kananaskis conference (Kendrick, 1971). The "Patterns of Development in Conidial Fungi" by Cole and Samson (1979) was helpful in our studies of some of the hyphomycetous fungi. The latest classification of fungi as outlined in Ainsworth & Bisby's Dictionary of Fungi by Hawksworth et al. (1995) is followed.

Various aspects of the taxonomy of thermophilic fungi remain to be worked out. The difficulty encountered in properly classifying, especially of the deuteromycetous fungi, is the evidence that the genera involved are in need of revision. However, the number of known thermophiles is still so less that, once their thermophilic character has been established, it will be a relatively easy matter, even for non mycologists, to identify future isolates by means of the simple key provided here.

KEY TO THE IDENTIFICATION OF THERMOPHILIC FUNGI

ZYGOMYCOTA

1 Mitospores endogenous, formed in sporangia; zygospores formed by hyphal conjugation; saprobic or, if parasitic or predaceous, having mycelium immersed in the host tissue	**Zygomycetes**	**2**
2 Sporangiophore arising from trophocyst; sporangia multispored, thallus mycelial	**Mucorales**	**3**
3 Sporangia columellate, specialized sporangiola absent; zygospores smooth to warty, borne on opposed, tongs-like or apposed, naked or appandaged suspensors; polyphyletic	**Mucoraceae**	**4**
4 Sporangia (sub)globose; short apophysis may be present; sporangiophores unbranched, originating from distinct rhizoids; sporangiospores often striate or angular	*Rhizopus*	

I Sporangiospores distinctly striate — *Rhizopus microsporus*
II Sporangiospores inconspicuously striate — *Rhizopus rhizopodiformis*
c Sporangia (sub)globose, apophysis absent; sporangiophores branched, not originating from distinct rhizoids; sporangiospores not striate or angular — *Rhizomucor*
Sporangiospores dumb-bell shaped — *Rhizomucor nainitalensis*
I Zygospores always present at 37°C; homothallic — *Rhizomucor miehei*
II Zygospores absent unless compatible matings are made; heterothallic — *Rhizomucor pusillus*

ASCOMYCOTA

1 Meiospores endogenous, formed in asci by free cell formation — **Ascomycetes** **2,10**
2 Ascomata cleistothecial, composed of flattened, hyaline to pale brown hyphae;asci scattered, evanescent at a very early stage; ascospores ellipsoid, smooth, hyaline; anamorph composed of simple basipetal thallic or blastic chains ofthick-walled conidia — **Eurotiales** **3**
3 Ascomata brightly colored, composed ofthick-walled pseudoparenchymatous tissue; asci often fonned in chains; ascospores usually yellowish, usually bivalvate, sometimes ornamented — **Trichocomaceae** **4,7**
4 Ascomata mostly confluent, crust-like, reddish — *Thermoascus, Dactylomyces*
Coonemeria **5**
5a Anamorph consisting of chlamydospores — *Thermoascus aurantiacus*
b Anamorph *Paecilomyces* or *Polypaecilum* **6**
6a I Anamorph *Paecilomyces crustaceus* — *Coonemeria crustacea*
II Anamorph *Paecilomyces aegyptiaca* — *Coonemeria aegyptiaca*
b Anamorph *Polypaecilum* — *Dactylomyces thermophilus*
7 Ascomata globose or subglobose, pale gray — *Talaromyces* **8**
8a Anamorph *Penicillium emersonii;* ascomata abundantly produced on agar media — *Talaromyces emersonii*
b Anamorph *Paeciolomyces byssochlamydioides;T. byssochlamydioides*
c Anamorph *Penicillium duponti;* ascomata rarely produced on agar media unless established cultures are flushed with N_2 **9**
9a Asci subglobose, scattered — *Talaromyces duponti*

b Asci globose to subglobose, produced in short chains — *Talaromyces thermophilus*

10 Ascomata perithecial or cleistothecial, thick-walled, fragmenting into well defined plates; asci persistent or evanescent; ascospores brown — **Sordariales 11,20,23,24**

11 Ascomata often hairy, ostiolate or nonostiolate; ascospores usually small, with minute germ pores — **Chaetomiaceae 12,17**

12 Ascomata perithecial — *Chaetomium* **13,15,16**

13 Perithecia with terminal hairs dichotomously branched; ascospores subglobose, 7-8 µm long — *Chaetomium thermophile* **14**

14a Perithecia gregarious — *C. thermophile var. coprophile*

b Perithecia scattered, only occassionally gregarious — *C. thermophile var. dissitum*

15 Perithecia with terminal hairs ribbon-like, somewhat twisted undulate; ascospores ovate or clavate bilaterally flattened, 9-11 x 7-8 x 6.7 µm — *Chaetomium senegalensis*

16 a Perithecia with terminal hairs irregularly branched or suggestive of dichotomous branching; ascospores almond-shaped, 9-11 µm long — *Chaetomium virginicum*

b Asci clavate, ascospore 5.5-7.8 x 5.2-6.3 µm — *C. mesopotamicum*

c Asci club-shaped, ascospores 19-24 x 11-14 µm — *C. britanicum*

17 Ascomata cleistothecial; ascospores ellipsoidal or ovoid — *Thielavia, Chaetomidium* **18**

18a Peridium pseudoparenchymatous; ascoma wall brown — *Thielavia minor*

b Peridium composed of *textura epidermoidea* — **19**

19a Ascoma wall light brown; asci globose, 10 µm — *Thielavia australiensis*

b Ascoma wall brownish to black; asci oval to pyriform, 16-19 x 25-35 µm — *Thielavia terricola*

c Ascomatal wall pseudiparenchymatous — *Chaetomidium pingtungium*

20 Ascomata not hairy, or with setae surrounding the ostiole; ostiolate or non-ostiolate; ascospores usually large, with conspicuous germ pores — **Ceratostomataceae 21**

21 Ascomatal wall composed of dark, flattened irregular, thick-walled cells; ascospores with two apicaf germ pores; anamorph *Myceliophthora* — *Corynascus* **22**

22a Heterothallic; ascospores 19-28 µm	*Corynascus thermophilus*
b Homothallic; ascospores 10.9 -19 x 6-10 µm	*Corynascus sepedonium*
23 Ascomata nonostiolate, wall glabrous composed of polygonal cells, dark brown	**Familiae incertae sedis**
a Ascospores globose or elliptical, with a single apiculus, 10-15µm	*Melanocarpus albomyces*
b Ascospores ovoid 7.5-9 x 6-7.5 µm	*Melanocarpus thermophilus*
24 Ascomata cleistothecial, ascoma wall made up of angular dark cells Ascospores greenish brown, with a subapical germ pore,14.0-18.0 x 7.5-10.0 µm	**Microascaceae** *Canariomyces thermophila*

DEUTEROMYCETES (ANAMORPHIC FUNGI)

1 Asexual reproduction usually by conidia; teliomorph absent	**Deuteromycetes**	**2**
2a Conidia absent; bulbils present	*Papulospora thermophila*	
b Conidia present		**3**
3a Conidiophores aggregated into synnematous conidiomata, with slimy conidial heads	*Remersonia thermophila*	
b Conidiophores thick walled	*Acremonium*	
I Conidia pyriform smooth 3-6 x 1-1.5µm	*Acremonium albamensis*	
II Conidia ellipsoidal 3-4 x 1.3-1.7 µm	*Acremonium thermophilum*	
c Conidiophores not aggregated into synnematous conidiomata,not with large slimy heads		**4**
4a Conidia (endo)arthric	*Malbranchaea cinnamomea*	
b Conidia not arthric		**5**
5a Conidia hyaline, not darkly pigmented	*Chrysosporium*	
I Conidia aleurosporic, borne terminally or laterally on the conidiogenous cells, pyriform to clavate, rough	*Chrysosporium tropicum*	
II Conidia formed terminally or laterally from almost all parts of the aerial mycelium on conspicuous relatively narrow pegs, globose or elliptical, smooth	*Myceliophthora fergusii*	

b Conidia hyaline to pale brown, produced singly or in short chains on ampulliform swellings, rough walled in fresh isolates	*Myceliophthora thermophila*	
c Conidia verrucose to spinulose	*Myceliophthora hinnulea*	
d Conidia brown to black		**6**
6a Conidia only in chains	*Scytalidium*	
I Conidia smooth, globose or oval shaped	*Scytalidium thermophilum*	
II Conidia thick walled, ellipsoid to barrel-shaped	*Scytalidium indonesicum*	
b Conidia mostly solitary , rarely in short chains		**7**
7a Conidia stellate *Arthrinium pterospermum*		
b Conidia not stellate		**8**
8a Conidia verrucose	*Thermomyces lanuginosus*	
b Conidia smooth		**9**
9 Intercalary chlamydospores absent	*Thermomyces ibadanensis*	

ZYGOMYCETES

Rhizomucor miehei (Cooney and Emerson) Schipper (1978)
Syn.: = *Mucor miehei* Cooney and Emerson (1964)

Heavy colony bearing numerous sporangia on YpSs agar at 35-45^{o}C. Colonies compact, at first white, later gray brown to biege brown. *Sporangiphores* 8 μm in width, loosely sympodially branched. *Sporangia* spherical, 30-60 μm in diameter, walls echinulate. *Columellae* spherical to oval, 20-45 μm in diameter. *Sporangiophores* nearly spherical, colourless, 4-6 x 3-5 μm. *Zygospores* in abundance, subspherical, warty, reddish brown or yellow when young, blackish at maturity, 30-50 μm in diameter, produced on homothallic mycelium.
Habitat: On retting guayule, soil and sand, coal mines, hay, stored barley, compost.
Distribution: USA, India, Ghana, UK and Saudi Arabia.
Description: Based on Schipper (1978)

Rhizomucor nainitalensis Joshi (1982)

Growth at 48°C is very rapid filling half of a Petri dish in 2 days. At 38 °C, "the growth of the mycelium takes place after three days but about one

week is required to colonize the culture medium in a petri dish at 25°C". *Rhizomucor nainitalensis* appears very close to *R. miehei.* It differs from *R. miehei* and *R. pusillus* mainly by sporangiospores of varying shapes and sizes. *Sporangiospores* subglobose, ellipsoidal, oblong, reniform, dumb-bell shaped, 3-6 µm or more wide.
Habitat: decomposed oak log.
Distribution: India.
Description: Based on Joshi (1982).

Rhizomucor pusillus (Lindt.) Schipper (1978)
Syn.: = *Mucor pusillus* Lindt (1886)
= *Rhizomucor parasiticus* Lucet & Cost. (1901)
= *Rhizomucor septatus* (Bezold) Lucet & Cost. (1901)
= *Rhizopus parasiticus* (Lucet & Cost.) Lendner (1908)
= *Mucor buntingii* Lendner (1908)
= *Mucor hagemii* Naumov (1935)

Colony growth on YpSs at 45^{o}C is very fast, initially white later becoming grayish with whitish margin, colour changes to grayish black at maturity, mycelial turf 2-3 mm high. *Sporangiophores* sympodially branched, 10-15 µm in diameter, colourless to yellow brown. *Sporangia* 50-80 µm in diameter, spinulose, rupturing at maturity, columellae subglobose to slightly elongate, 15-35 µm in diameter and up to 60 µm long. *Sporangiospores* colourless, globose to sub-globose, 3-5 µm in diameter. Chlamydospores absent. *Zygospores* produced in compatible (heterthallic) isolates on YpSs and MEA at 30-40 ^{o}C, reddish brown to black, warty, 45-70 µm in diameter.
Habitat: Mainly on composting and fermenting substrates like compost, municipal wastes, horse dung, composted wheat straw, guayule, hay, seeds of cacao, barley, oat, maize and wheat, groundnuts, peacans, sputum, bird's nests, air and soil.
Distribution: UK, Chad, Czechoslovakia, South Africa, Indonesia, India, Japan, USA, Nigeria and Australia.
Description: Based on our isolates IMI 339616, 318201 and 333312.

Rhizopus microsporus van Tieghem

Growth at 45^{o}C on YpSs is extremely rapid. Colonies cottony, turf high, at maturity grayish black, vegetative mycelium hyaline. This fungus is characterised by the production of stolons. Rhizoids pale brown, 60-170 x 4-7 µm. *Sporangiophores* unbranched, arise singly or in groups from reduced

nodal regions, smooth, hyaline to pale brown, 400-1400 x 15-30 μm, up to 40 μm at the base. *Sporangia* black, usually moist, globose, smooth, 40-90 μm in diameter. Each sporangium possesses a broad oval columellae. *Sporangiospores* numerous, pale brown, striate, oval, 5-8 μm in diameter. *Zygospores* rarely produced.
Habitat: Soil, composting wheat straw, coal mine soils, fermenting plant materials, nesting materials, stored grains, air and cow dung.
Distribution: India, Sudan, Tanzania, Malaysia and Australia.
Description: Based on our isolate IMI 339612.

Rhizopus rhizopodiformis (Cohn.) Zopf

Growth very rapid at 45^{o}C on PDA filling a 90 mm Petri dish in 24 hr. Colony white at first later grayish black. Vegetative hyphae hyaline, 3-7 μm in diameter, reduced stolons. *Rhizoids* pale brown, 120-150 x 12-14 μm. *Sporangiophores* arise singly, in twos or in-groups from the reduced nodal regions. *Sporangia* black, spherical, smooth, 76-175 μm in diameter. *Sporangiospores* pale brown, spherical, smooth, 3-6 μm in diameter.
Habitat: Coal mine soils, nesting material of birds, lung of pullet, stomach of pig, bread, wooden slats, soil, seeds of *Lycopersicon esculentum*, *Cucumis melo*, breeder cow, oil palm effluents.
Distribution: India, UK, South Africa, China, Ghana, Hong Kong, Indonesia, Malaysia and Japan.
Description: Based on Thakre and Johri (1976).

ASCOMYCETES

Canariomyces thermophila Guarro & Samson in von Arx, Figueras & Guarro (1988)

Growth of the fungus takes place at 45^{o}C but no data on minimum and maximum growth temperature is available. *Ascomata* cleistothecial, ascoma wall made up of angular dark cells. *Asci* irregularly disposed. *Ascospores* greenish brown when mature with a subapical germ pore, 14.0-18.0 x 7.5-10.0 μm. No anamorph is reported.
Habitat: Soil,
Distribution: Africa
Descriptions: von Arx, Figueras & Guarro (1988)

Chaetomidium pingtungium (Chen & Chen) Mouch., in Johri, Satyanarayana & Olsen (eds.) 1996
Syn.: = *Thielavia pingtungia* Chen & Chen (1996)

Growth at 48°C fairly good but no growth between 25 and 30°C. The species is characterized by dark globose cleistothecia covered with brown thick-walled hairy appendages, *ascomatal hairs* echinulate, 2.5-4.0 µm wide and up to 350 µm long, ascomatal wall pseudoparenchymatous. *Asci* cylindrical, 40-52 x 7-9 µm, stipitate, fasciculate, 8-spored. *Ascospores* usually limoniform with pointed ends and elliptical in side view, uniseriate, dark brown, smooth, thick-walled, 8.5-10.0 x 6.5-8.5 µm. No anamorph stage developed in cultures.
Habitat: Sugarcane field.
Distribution: Taiwan.
Description: Based on Chen & Chen (1996)

Chaetomium britannicum Ames (1963)

Growth of the fungus and production of perithecia takes place at 47°C. *Ascomata* ovoid to vase-shaped. Terminal and lateral hairs are very slender, greyish, straight to undulate. *Asci* club-shaped, 8-spored. *Ascospores* brown, large, 19-24 x 11-14 µm, irregularly oval, rounded on the ends and has a single apical germ pore.
Habitat: Mushroom compost, soil,
Distribution: UK
Descriptions: Based on Ames (1963)

Chaetomium mesopotamicum Abdullah & Zora (1993)

This is a newly described species and has a growth temperature range from 30-52°C. It differs from *Chaetomium thermophilum* LaTouche and *C. virginicum* Ames by its *asci*, which are clavate and possess long highly branched terminal hairs. *Ascospores* globose to ovoid, olive to brown, 5.5-7.8 x 5.2-6.3 µm, provided with one apical germ pore.
Habitat: Date palm plantation.
Distribution: Iraq.
Description: Based on Abdullah and Zora (1993).

Chaetomium senegalensis Ames (1963)

Colonies on YpSs at 45°C appear white with a daily growth rate of 6-7 mm. Yellow exudate in mature colonies appears after 18-20 days. *Ascomata* dark, spherical or ovate, ostiolate, 110-230 μm in diameter, with a dark brown or black wall of angular, flattened, 6-10 μm cells. *Ascomatal hairs* narrow, delicate, often branched with bulbous base and tapering ends, punctulate or verrucose, 1.5-2 μm in width. *Asci* fasciculate, narrow, cylindrical, 8-spored, 50-70 x 7-9 μm. *Ascospores* uniseriate, ovate or clavate, bilaterally flattened, dark greenish, brown when mature, 6.5-12.5 x 4-7 μm, tear drop shaped with a sub-apical germ pore.
Habitat: On plant remains, seeds of *Capsicum annuum*, soil, decomposing wheat straw.
Distribution: Senegal, Netherlands, Kuwait, Iran and India.
Description: Based on our isolates IMI 348709 and 364220.

Chaetomium thermophile **var. *coprophile*** Cooney and Emerson (1964)

On YpSs agar at 45°C, the colonies appear white at first producing typical concentric rings of growth, the rings of dark brown perithecia separated by narrow zones of whitish hyphae. *Perithecia* superficial, more or less gregarious, globose or subglobose, 75-150 μm in diameter, ostiolate, but the ostiole is not easily observed, as the perithecia are densely clothed with dark, dichotomously branched hairs. Hairs smooth, 40-140 x 4.5-7 μm. *Asci* short stalked, cylindrical, produced in a basal tuft, bear eight spores in a linear row, 45-55 x 6-8 μm. *Ascospores* dark or olive brown, globose or subglobose, 7-9 μm in diameter.
Habitat: Decomposing wheat straw, horse dung, mushroom compost, vegetable detritus and soil.
Distribution: USA, UK, India, Netherlands, Ghana.
Description*: Based on our isolate IMI 348710*

Chaetomium thermophile **var. *dissitum*** Cooney and Emerson (1964)

On YpSs agar at 45°C, the colonies appear colourless at first then become dark brown. Perithecial initials appear in about two days as small, colourless knots on the hyphae. *Perithecia* superficial, gray, gray-green to dark brown, produced in diffuse manner, scattered, ostiolate but the opening is not easily observed as the perithecia are densely clothed with dense terminal hairs, mature perithecia 60-175 μm in diameter, usually globose, although

subglobose or oval forms are also quit common. *Asci* short stalked, cylindrical, 8-spored arranged in a single row, 50-60 x 7-8 μm. *Ascospores* olive brown in colour, globose or subglobose, smooth walled, 6.5-9.5 μm in diameter, with a single apiculus.
Habitat: Nesting materials, decomposing wheat straw, mushroom compost, and soil.
Distribution: USA, UK, India, Netherlands and Ghana.
Description: Based on our isolate maintained in our culture collection under accession number T 132.

Chaetomium virginicum Ames (1963)

Colonies appear rich brown in colour at 45^{o}C, hyphae 2-4 μm wide, often anastomose to form a loose network. *Perithecia* brown, globose, attached to the substratum with undifferentiated rhizoids, terminal hairs cover the entire perithecium giving it the appearance of a tumbleweed in miniature. Hairs dense, granular, intricate, irregularly branched or suggestive of dichotomous branching. *Asci* stalked, long, cylindrical, 8-spored, 70 x 10 μm. *Ascospores* unistichous, light yellow brown to pale brown, almond shaped, 8-11 μm.
Habitat: On decomposing leaves
Distribution: USA
Description: Based on Ames (1963)

Corynascus sepedonium (Emmons) von Arx (1975)
Syn.: = *Thielavia sepedonium* Emmons (1932)
= *Thielavia lutescens* Kamyschko

Conidia produced as solitary or catenulate aleurioconidia, globose, tuberculate, echinulate, bright yellow in enmass, 4-12 μm in diameter. *Ascocarps* globose, olivaceous to black, glabrous, 20-150 μm in diameter. *Asci* ovoid, irregularly disposed, not borne on croziers, stipitate at first but often not so as the ascocarps enlarge, 8-spored, 25-35 x 17-25 μm. *Ascospores* ellipsoidal, slightly flattened on one side, with a germ pore at each end, dark brown, 10.9- x 6-10 μm.
Habitat: Dung, soil, human skin, pasture soil, hay, coal spoil tips, compost, cellulose material, *Litchi sinensis* leaf, seeds of *Triticum, Foeniculum vulgare, Carpentaria acuminata.*
Distribution: India, Kenya, USA, Uzbekistan, UK, Ghana, Egypt, Hungary, Australia, China and Senegal.
Description: Based on von Arx (1975)

Corynascus thermophilus (Fergus and Sinden) von Arx (1975)
Anamorph = *Myceliophthora fergusii* (van Klopotek) van Oorschot (1977)
Syn.: = *Thielavia thermophila* Fergus and Sinden (1969)
= *Chrysosporium fergusii* van Klopotek (1974a)
= *Chaetomidium thermophilum* (Fergus & Sinden) B. Lodha (1978)

Colonies at 45^{o}C on starch yeast extract, cornmeal, and Czapek-yeast extract agars white and floccose. Mycelium immersed and superficial, aerial hyphae become powdery with masses of conidia. *Hyphae* hyaline, irregularly 3-septate, 2-10 µm wide. *Cleistothecia* globose, glabrous, black at maturity, nonostiolate, 190-260 µm in diameter. *Asci* hyaline, globose to oval, irregularly arranged. The ascus wall disappears while the ascospores are hyaline, and they subsequently become pink light brown, and finally dark brown, 4-spored, 37 x 40 µm. *Ascospores* brown, ellipsoidal, unicellular with a germ pore at each end, 19 x 28 µm in diameter.
Habitat: Mushroom compost.
Distribution: USA.
Description: Based on Fergus and Sinden (1969)

Coonemeria aegyptiaca (Ueda & Udagawa) Mouchacca (1997)
Basionym = *Thermoascus aegyptiacus* Ueda & Udagawa (1983)
Anamorph = *Paecilomyces aegyptiaca* Ueda & Udagawa (1983)

Growth of the fungus takes place between 25 to 55°C. At 40°C colonies fill the Petri plate within 4 days producing numerous superficial ascocarps, often forming a crusty mass, vinaceous to reddish brown, initials a simple coiled hyphae. C*onidia* fairly abundant, grayish yellow and not affecting colony color. *Cleistothecia* superficial, subglobose, orange-brown, 250-550 µm wide. *Asci* borne singly on croziers, scattered in the ascomatal cavity, 8-spored, ovate, 14-18 x 11-15 µm, evanescent. *Ascospores* single celled, ellipsoid to ovoid, yellowish to pale reddish orange, 6.0-8.5 x 4.0-5.5 µm, thick-walled and nearly smooth. *Conidiophores* erect arising more commonly from aerial hypae, hyaline, smooth-walled, 50-300 x 5-7 µm; apical parts irregularly branched and bearing terminal verticils of 2-4 phialides usually without any metulae. *Phialides* solitary or irregularly verticillate, cylindric, 12-30 x 3-6 µm. *Conidia* sometimes ovoid to subglobose formed in long divergent or tangled chains, continuous, hyaline but fulvous in mass, cylindrical to elliptical, 4.5-11 x 3-4 µm.
Habitat: Sludge and soil.
Distribution: Egypt and Iraq.

Description: Mouchacca (1997)

Coonemeria crustacea (Apinis & Chesters) Mouchacca (1997)
Anamorph: = *Paecilomyces crustaceus*
Syn.: = *Dactylomyces crustaceus* Apinis & Chesters (1964)
=*Thermoascus crustaceus* (Apinis & Chesters) Stolk (1965)

Colony growth on malt agar at 45^{o}C is rapid. Hyphae hyaline, septate 2-12 μm in diameter. *Conidiophores* hyaline, septate, smooth, produced mainly from the submerged mycelium but also from trailing hyphae, conidiophores up to 1000 μm long, with a diameter of 7-12 μm at the base and tapering to 4-5 μm at the apex, the upper part bears irregularly arranged branches. *Phialides* occur either singly as side branches, or they appear in irregular verticils of two or three at the end of the branches, 15-30 μm long, consisting of cylindrical basal part, 5-7 μm in diameter, tapering gradually to a long conidium bearing tube, slightly bent away from the main axis, up to 12 μm long and about 3 μm in diameter. *Conidia* smooth, hyaline to pale brown, produced in conspicuous, long, diverging chains, cylindrical when young, ellipsoidal when mature, 6-10 x 3-6 μm. *Ascocarps* usually confluent or globose when borne separately, 300 –900 μm in diameter. *Asci* subglobose, produced singly by means of croziers, mostly 8-spored, 16-20 x 13-15 μm. *Ascospores* oval, yellow to pale brown, ascospore wall show fine echinulations, 6.5-8 x 5-6.5 μm.
Habitat: Coal spoil tips, bagasse and soil.
Distribution: USA, UK, Ghana, Japan, Netherlands and Indonesia.
Description: Based on Stolk (1965) and Mouchacca(1997).

Dactylomyces thermophilus Sopp (1912)
Anamorph = *Polypaecilum* sp. (Apinis) 1967
Syn.: = *Thermoascus thermophilus* (Sopp) von Arx (1975)
= *Penicillium thermophilus* (Sopp) Biourge
= *Penicillium thermophilum* (Sopp) Saccardo

Hyphae hyaline, branched, septate, 2-15 μm thick. *Conidiophores* smooth, dichotomously branched, robust and hyaline, conidiophores are usually twisted and arise from either creeping surface hyphae or trailing aerial hyphae, up to 25 μm in diameter, conidiophore tips bear a lobed or palmate anellophore. *Conidia* produced in chains, non-septate, smooth, cylindrical to oval, green or yellow green in mass, hyaline or sub-hyaline, 3-11 x 2.5-5.5 μm. *Ascocarps* superficial, firm, irregularly globose, red-brown, more or less solitary, 150-600 μm in diameter. *Asci* subglobose to oval, evanescent, 8-

spored, 12-15 μm in diameter. *Ascospores* hyaline, non-septate, smooth, more or less oval, 5.5-8 x 3.5-6 μm.
Habitat: Wood and bark of *Pinus*, plant debris.
Distribution: Sweden, Norway and UK.
Description: Based on Apinis (1967)

Melanocarpus albomyces (Cooney and Emerson) von Arx (1975)
Syn.: = *Myriococcum albomyces* Cooney and Emerson (1964)
= *Thielavia albomyces* (Cooney & Emerson) Malloch & Cain (1972)

On YpSs agar, colony appear white and cottony in the early stages becoming grayish black by fourth day and grayish black pigment excretyed in the agar medium. Two distinct types of hyphae: *aerial hyphae* septate and variable in thickness 2-10 μm wide; *prostrate hyphae* constricted at the septa, forming branched, chain like series of cylindrical or oval thick walled cells that break apart easily. *Ascocarps* superficial, dark brown, scattered or gregarious, globose, glabrous wall, nonostiolate, 150-250 μm in diameter. *Asci* pyriform when young, at maturity irregularly oblong, 8-spored, ascus membrane simple, very thin, evanescent, 35-40 x 15-20 μm. *Ascospores* single celled, smooth, dark brown, globose or elliptical, with a single apiculus, irregularly distributed in the ascus, 10-15 μm in diameter.
Habitat: Nesting material of chickens, decomposing wheat straw, soil and grass compost.
Distribution: USA, India, UK and Saudi Arabia.
Description: Based on our isolate maintained in our laboratory in our culture collection under accession number T 178.

Melanocarpus thermophilus (Abdullah & Al-Bader) Guarro, Abdullah & Al-Bader (1996)
Basionym: = *Thielavia minuta* (Cain) Malloch & Cain *var*. *thermophila* Abdullah & Al-Bader (1972)

Not much data on the growth profile of this fungus exist in literature. This ascomycete produces not the arthroconidial anamorph characteristic of the type species. *Asci* are 8-spored with *ascospores* being ovoid, dark brown, 7.5-9.0 x 6.0-7.5 μm, each provided with a single germ pore.
Habitat: Forest soil.
Distribution: Iraq.
Description: Guarro *et al.* (1996).

Talaromyces byssochlamydioides Stolk & Samson (1972)
Anamorph = *Paecilomyces byssochlamydioides* Stolk & Samson (1972)

The optimum growth of the fungus takes place at 40-45^{o}C. It is mainly distinguished by its conspicuous *Paecilomyces* anamorph having cylindrical conidia. *Ascomata* always develops in culture concomitantly with the anamorph and as such prevents its confusion with the similar imperfect taxon of *Paecilomyces variotii* Bainier. *Ascospores* globose to subglobose, 3.7-4.5 x 3.5-4.0 µm, thick-walled smooth, often partially covered by remnants of a gelatinous covering material.
Habitat: Soil.
Distribution: Japan and Egypt.
Description: Stolk & Samson (1972); Awao & Otsuka (1974).

Talaromyces duponti Griffon and Maublanc (1911)
Anamorph = *Penicillium dupontii* Griffon & Maublanc(1911) Raper & Thom (1949)

On yeast glucose agar at 45^{o}C growth is fairly rapid. Colony initially white, changing to dull grayish green, lavender or pinkish brown. Hyphae delicately branched, septate, 2-3 µm in diameter. *Conidiophores* short, lateral, more or less perpendicular to the main hyphae, simple or branched, septate, 5-30 x 2-3 µm, tapering slightly towards the base. *Penicilli* irregular, monoverticillate with 1 to 4 phialides to partially or nearly regularly biverticillate. *Metulae* 5-7 x 2-3 µm. *Phialides* acuminate, divergent, 8-10 x 2 µm. *Conidia* pale yellow, ovoid to elliptical, smooth, 2-5 x 1.5-3 µm. *Cleistothecia* grayish tan, subspherical, mostly scattered, 400-1300 µm in diameter, peridium distinct, smooth papery, nonostiolate. *Asci* scattered, subglobose, 8-spored, evanescent, 9-10 µm in diameter. *Ascospores* lenticular, pale yellow, with a well-defined equatorial furrow, flanked by low, smooth or somewhat jagged ridges, 3-5 x 2.5-3.5 µm.
Habitat: Manure and damp hay, self-heated guayule shrub, leaf litter, soil, cigarette and *Hordeum vulgare*.
Distribution: USA, India, UK, France, South Africa, Netherlands, Jordan and Nigeria.
Description: Based on Cooney and Emerson (1964).

Talaromyces emersonii Stolk (1965)
Anamorph: *Penecillium emersonii* Stolk (1965)
Syn.: = *Geosmithia emersonii* (Stolk) Pitt (1979)

= *Byssochlamys* sp. *fide* Cooney & Emerson (1964)

Colonies on malt agar growing rapidly, attaining a diameter of 5-7 cm in seven days at 45°C. Mycelium hyaline, partly submerged, partly aerial, appearing definitely funiculose, producing colourless to cream exudate in droplets. *Ascocarps* produced in dense yellow to reddish brown layer. *Hyphae* hyaline, 1-3 μm in diameter. *Conidiophores* arising from the funiculose aerial mycelium, hyaline to pale brown, erect, septate, 35-150 x 3-4.5 μm, conidiophores usually with one to two branches, densely compacted. *Phialides* almost cylindrical with abruptly tapering tip, upto 2 μm in length, all elements of the conidiophores appear roughened. *Conidia* mostly cylindrical, occasionally ellipsoidal, smooth, hyaline to pale brown, 3.5-5.0 x 1.5-2.5 μm, produced in long, loosely adherent to parallel chains, often forming loose columns. *Ascocarps* often confluent, but when borne separately, they are globose to ellipsoid, 50-300 μm in diameter. *Asci* evanescent, subglobose to ellipsoid, 8-spored, 8-9 x 6-8 μm. *Ascospores* yellow, thick walled, wall smooth, subglobose to ovoid, 3.5-4.0 x 3-3.5 μm.
Habitat: Compost, soil, piles of wood chips, river banks, grassland, municipal waste, peat, coal spoil tips, sugarcane bagasse, palm oil kernels, Blesbok dung, air, rhizosphere of *Cassia tora*, and *C. occidentalis*.
Distribution: Italy, Netherlands, UK, USA, Sweden, Canada, Japan, India, Nigeria and South Africa, Indonesia.
Description: Based on Stolk (1965).

Talaromyces thermophilus Stolk (1965)
Anamorph: *Penecillium duponti* Raper and Thom (1949)

Colonies on malt agar grow rapidly at 45°C. Mycelium floccose to slightly funiculose producing abundant conidial structures in gray brown colours. *Hyphae* hyaline, septate, 2-3 μm in diameter. *Conidiophores* borne as perpendicular branches from aerial hyphae, smooth walled, short, 2-30 x 2-3 μm, slightly inflated at apex, 4 μm in diameter. *Phialides* in small clusters of four in verticil, divergent, swollen at base, tapering abruptly to a long conidium bearing tip, 7-10 x 2-2.5 μm. *Conidia smooth*, ovoid to ellipsoidal, 2.5-5 x 1.5-3 μm. *Ascocarps* pale gray, globose to subglobose, non-confluent, 400-1300 μm in diameter. *Asci* produced in short chains, globose to subglobose, 9-10 μm in diameter. *Acospores* lenticular, ornated by two to three or more, somewhat jagged, irregular ridges, yellow, 3.5-5 x 2.5-3.5 μm.
Habitat: Guayule shrub, fermented straw, dung, compost, soils.
Distribution: USA, Netherlands, India, UK, Japan, Australia and Indonesia.

Description: Based on Stolk (1965).

Thermoascus aurantiacus Miehe (1907)
Syn.: = *Dactylomyces thermophilus* Sopp (1912) Cooney & Emerson (1964)
= *Thermoascus isatschenkoi* Cooney & Emerson (1964)

Growth on YpSs at 45^{o}C is very rapid and extends outward to fill a 90 mm Petri dish in two to three days. At first the hyphae are largely within the substratum or closely spread over the surface. Colony white in the early stages, later becoming very pale gray-buff. *Hyphae* colourless, septate, 1.5-12 μm wide. *Conidiophores* erect, septate, irregularly branched, up to 1000 μm long, tapering from 10-12 μm in diameter at the base to 5 μm at the apices. *Phialides* flask-shaped, sometimes branched, irregularly arranged 15-28 x 3-7 μm. *Conidia* colourless to pale brown, elliptical, produced in long chains, 3-8 x 2-6 μm in diameter. *Cleistothecia* reddish brown, irregular, globose or somewhat angular, scattered or partly confluent, 0.6-1.5 mm in diameter, peridial wall dull, rough, composed of several layers of pseudoparenchymatous cells. *Asci* numerous, scattered, oval, 8-spored, evanescent, 10-15 x 8-12 μm. *Ascospores* oval or elliptical, hyaline, single celled, smooth walled, with a characteristic germ pore, 6-8 x 5-6 μm.
Habitat: Heated hay, peat, cacao husks, mushroom compost, stored grains, coal mine soils, soil, air, self-heated wood chips, chaff, tobacco, sawdust.
Distribution: Germany, USA, India, Russia, Holland, Netherlands, South Africa, Italy, UK, Canada, Jordan, Australia, Indonesia, Egypt and Japan.
Description: Based on our isolate maintained in our culture collection under accession no. T -167.

Thielavia australiensis Tansey and Jack (1975)

Colonies on YpSs agar at 40^{o}C are sparse, colourless, mycelium of septate, branched hyphae, the agar is stained fulvous by a diffusible pigment. *Ascocarps* produced in abundance, scattered and immersed within the agar medium, globose, nonostiolate, glabrous, yellow-brown (appearing black when containing mature ascospores), 20-200 μm in diameter, with a peridium of textura epidermoidea and produced from mature asci. *Asci* globose, irregularly distributed, 8-spored, evanescent, 10 μm in diameter. *Ascospores* brownish-black, black in mass, ovoid, occasionally irregular in shape, with a single apical germ pore, 4-5 x 5-8 μm. *Conidia* are aleurioconidia of the form genus *Chrysosporium*, borne singly along the length of hyphae, single celled, sessile, ovoid, smooth, colourless, 3-5 x 5-8 μm.

Habitat: Nesting material of mallee fowl.
Distribution: Australia.
Description: Based on Tansey and Jack (1975)

Thielavia minor (Rayss and Borut) Malloch and Cain (1973)

Colony on YpSs agar broadly spreading, composed of white, cottony, aerial and submerged hyphae, 2-5 μm in diameter. *Ascocarps* spherical to globose, walls brown, nonostiolate, non-appendaged, brownish to almost black at maturity, 80-160 μm in diameter. *Asci* oval to globose, 8-spored, 15-18 x 10-14 μm. *Ascospores* broadly fusiform to elliptical, apiculate at both the ends, olive-brown, irregularly arranged, 10-12 x 13-15 μm.
Habitat: Coal mine soils, Elaeis guineensis leaf and groundnut kernels.
Distribution: India, Zaire and Zambia.
Description: Based on Malloch and Cain (1973).

Thielavia terricola (Gilman and Abbott) Emmons (1930)

Colonies on YpSs agar at 45^{o}C broadly spreading, composed of white, cottony aerial and submerged hyphae, 1-6 μm in diameter, branches constricted at base, homothallic. *Ascocarps* spherical, arise from an ascogonial coil, nonostiolate, brownish to black at maturity, colour largely due to masses of dark spores inside, 100-250 μm in diameter, outer wall of cleistothecium composed of uninucleate, rather thick walled cells, somewhat carbonized, inner wall of cleistothecium composed of thin walled, flattened cells. *Asci* oval to pyriform, 16-19 x 25-35 μm, deliquescing within the cleistothecium. *Ascospores* fusiform or elliptical, slightly apiculate at both the ends, dark olivaceous to brown, 7-9 x 10-16 μm, with a wall much thickened at the end opposite the germ pore.
Habitat: Soil, cow dung, compost and *Ficus* sp.
Distribution: USA, China, India, Canada, Kenya, Australia, UK and Indonesia.
Description: Based on our isolate IMI 310851.

DEUTEROMYCETES (ANAMORPHIC FUNGI)

Acremonium alabamense Morgan-Jones (1974)
Teleomorph: =*Thielavia terrestris* (Apinis) Malloch & Cain (1973)

The fungus produces fast growing colonies at high temperature. *Colonies* velvety, whitish, with yellowish to brownish runner hyphae which are 3-4.5 µm wide. *Conidiophores* are simple, short, 8-25 x 1-1.5 µm. *Conidia* are obovoid to pyrfiorm, smooth, with a truncated base, 3-6 x 2-3 µm.
Habitat: Alluvial soil, needles of *Pïnus taeda.*
Distribution: USA and UK
Description: Morgan-Jones (1974)

Acremonium thermophilum Gams & Lacey (1972)

Growth at 20°C is strong but slow, very good growth takes place between 25 and 40°C and very weak at 47°C. The fungus is regarded as unique among known *Acremonium* species on account of its thermophilic habit and production of submerged hyphae and having partly pigmented walls. *Conidiophores* thick-walled with basitonous ramification. *Conidia* are ellipsoidal, 3.0-4.0 x 1.3-1.7 µm
Habitat: Sugarcane bagasse
Distribution: Trinidad
Description: Gams and Lacey (1972)

Arthrinium pterospermum (Cooke & Massee) Arx (1981a)
Syn.: = *Humicola stellata* Bunce (1961)
= *Thermomyces stellatus* (Bunce) Apinis (1963)

Colonies on YpSs agar at 37^{o}C dull black. Hyphae colourless, septate, about 2 µm in diameter. *Conidiogenous cells* short up to 3 µm long, arising at right angle to the filaments. *Conidia* single on each conidiogenous cell, subglobose and colourless when young, becoming dark brown and stellate at maturity, 7.6 x 5.3 µm, separating from the conidiogenous cell and commonly retain a short attachment piece.
Habitat: Moldy hay and soil.
Distribution: UK and USA.
Description: Based on Apinis (1963)

Chrysosporium tropicum Carmichael (1962)

Colony growth on YpSs at 45^{o}C flat, granular in texture, dry, white to cream in clour. *Mycelium* hyaline septate, smooth-walled, 2-4 µm in diameter. *Conidiophores* poorly differentiated. *Conidia* borne at the tips of the hyphae, directly along the sides or on short or long lateral branches, aleurosporic.

Intercalary conidia also occur. Conidia hyaline, pyriform to clavate with a broadly truncate base and smooth or inconspicuous roughened walls, 3-5 x 4-9 μm.
Habitat: Deteriorating woolen fabric, dung, soil and air.
Distribution: New Guinea, India, USA and Canada.
Description: Based on our isolates IMI 318198, 339617.

Malbranchea cinnamomea (Libert) van Oorschot & de Hoog (1984)
Syn.: = *Malbranchea sulfurea* (Miehe) Sigler and Carmichael (1976)
= *Malbranchea pulchella* var. *sulfurea* (Miehe) Cooney and Emerson (1964)
= *Thermoideum sulfureum* Miehe (1907)

At 45°C, colonies on YpSs are robust, dense, thick, smooth or with a few outward radiating folds, velvetty with coarse, creamy yellow tufts of hyphae, sulfur yellow. The medium turns dark brown or black from diffused pigment. *Vegetative hyphae* hyaline, later becoming yellowish-brown with prominent racket hyphae, swelling near the septum to a diameter of 9 μm or more. *Arthroconidia* borne on curved or loosly coiled lateral branches arising from broader vegetative hyphae, 3-6 μm in diameter. *Conidia* cylindrical, often curved, thick walled, often with attached hyaline frill from the outer hyphal wall of the separating empty cell, hyaline, later yellow, tan or yellowish green, 3-4.5 x 4-7 μm.
Habitat: Guayule rets, composting heaps, wheat straw compost, stacked tobacco leaves, soil, peanut kernels, coal spoil tips, feaces of Cape sparrow, deer dung, cattle, hen-house litter, snuff, air and silage.
Distribution: USA, Germany, UK, South Africa, Japan, Canada, Netherlands, Australia, Ghana, Egypt, India and Indonesia.
Description: Based on our isolate IMI 361367.

Myceliophthora fergusi (van Klopotek) van Oorschot (1977)

Growth on YpSs at 45°C very rapid, densely floccose, granular, creamy, colony margins irregular, feather like in appearance and with age becomes mealy or dirty yellow as the aerial mycelium dies down and very old colonies have a dark brown reverse. Aerial mycelium hyaline, septate, smooth walled, 2-4.5 μm in diameter. *Conidiophores* poorly differentiated from the mycelium. *Conidia* formed terminally and laterally from almost all parts of the aerial mycelium on conspicuous relatively narrow pegs. Conidia hyaline, smooth,

truncate, round (3.7-7.5 μm) or elliptical (5.5-11 x 4.5 μm). *Chlamydospores* in chains of globose swellings, dark brown, abundant in older cultures.
Habitat: Soil.
Distribution: India
Description: Based on our isolates IMI 364225 and UAMH 8054.

Myceliophthora hinnulea Awao & Udagawa (1983)

Growth of the fungus is extremely reduced at 20°C, optimal growth takes place at 40-45°C and maximum slightly above 50°C. *Colonies* mainly dull to greyish brown. *Conidia* brownish, conspicuously verrucose to spinulose, 8.0-10.0 x 6.0-7.5 μm.
Habitat: Cultivated soil.
Distribution: Japan.
Description: Awao and Udagawa (1983).

Myceliophthora thermophila (Apinis) van Oorschot (1977)
Teleomorph : *Corynascus heterothallicus* (van Klopotek) von Arx (1981)
Syn.: = *Sporotrichum thermophile* Apinis (1963)
= *Chrysosporium thermophilum* (Apinis) van Klopotek (1974b)
= *Myceliophthora indica* Basu (1984)

Growth at 45^{o}C on CDA is very rapid. Colonies dry, thin, broadly spreading with a surface texture that varies from floccose or cottony to granular or powdery. The colour is at first white, then pink, buff, and finally fulvous or cinnamon brown. *Hyphae* colourless, about 2 μm broad. *Aleuriospores* terminal or lateral on the hyphae or on short stalks, which may be ampulliform, occassionally catenate, mostly ovate or pyriform or strongly clavate with abroad or narrow scar, thick walled, smooth or variously encrusted, orange brown, 4-8 x 2-4(5) μm.
Habitat: Soil.
Distribution: USA, Canada, India, UK, Japan and Australia.
Description: Based on van oorschot (1977).
Papulospora thermophila Fergus (1971)

Colonies on YpSs at 45^{o}C white and downy, margins possess closely spaced indentations. *Mycelium* of two types, one very narrow, 1.5 μm in diameter, sparingly septate and moderately branched, the other wide, 5-7.5 μm in diameter, regularly septate and much branched. *Bulbils* produced on aerial hyphae and on submerged hyphae, those on the aerial hyphae are globose to

subglobose and average 105 x 90 μm in diameter, those formed on submerged hyphae are irregular in shape, and average 125 x 113 μm in diameter. They are white at first, then become yellow and finally orange at maturity. The outer three layers of the mature bulbils are formed of narrow and elongate cells while the interior of globose cells and are lighter in colour. The bulbils begin to form after 24 hr. incubation at 45^{o}C.
Habitat: Mushroom compost and soil.
Distribution: Switzerland, India and Japan.
Description: Based on Fergus (1971).

Scytalidium indonesicum Hedger, Samson and Basuki (1982)

The growth of the fungus is very rapid at 45°C filling the 90 mm Petri dish in about 36 hours. The fungus is distinguished by the production of intercalary conidia (chlamydospores). *Conidia* thick-walled, brown, ellipsoid to barrel-shaped, often with irregular outgrowths and also often constricted at the middle of the cell, 15-25 x 7-12 μm. On maturity these conidia secede rather easily and appear irregular in shape. Dark brown and thick-walled similar but less wider conidia (arthroconidia) also develop in chains, 13-32 x 5-8 μm and these do not secede easily.
Habitat: Soil and *Dipterocarp* forest soil.
Distribution: Indonesia, Java and Sumatra.
Description: Hedger *et al*. (1982)

Scytalidium thermophilum (Cooney and Emerson) Austwick (1976)
Syn.: = *Torula thermophila* Cooney and Emerson (1964)
= *Humicola insolens* Cooney & Emerson (1964)
= *Humicola fuscoatra* var. *longispora forma insolens* Cooney & Emerson (1964)
= *Humicola grisea* Traaen var. *thermoidea* Cooney & Emerson (1964)
= *Humicola insolens* Cooney & Emerson var. *thermoidea* Ellis (1982).
= *Scytalidium allahabadum* Narain, Srivastava & Mehrotra (1983)

Colonies on YpSs agar at 45^{o}C are white at first but soon turns through grayish to jet-black as spore maturation proceeds. Hyphae colourless, prostrate, branched, septate, 2-5 μm wide. *Conidiogenous cells* small, 8.7 x 3.7 μm. *Conidia* dark brown, smooth walled, translucent, generally globose, 7-12.5 μm in diameter, or oval 11.2-14.6 x 7.5-10 μm, produced basipetally in chains on hyphal branches or developed intercalarily.

Habitat: Nesting litter of chickens, mushroom compost, soil, horse dung and wood chips.
Distribution: USA, Japan, Indonesia, India, UK and Netherlands.
Description: Based on our isolate IMI 361370.

Remersonia thermophila (Fergus) Seifert & Samson (1997)
Syn.: = *Stilbella thermophila* Fergus (1964)

Colonies on YpSs at 45^{o}C are discrete. *Mycelium* mostly submerged, composed of brownish gray, aggregated hyphae, superficial mycelium septate, smooth, 2-4 μm in diameter. *Synnemata* parallel, determinate, conspicuous, distinct, superficial, erect, grayish brown to pale brown up to 450-600 μm long, 7-60 μm wide at the base, 18-120 μm wide at the convex apex. Constituent hyphae usually unbranched, smooth, septate, pale brown, 2-3 μm wide, compacted together at the base then splaying out to form a wide convex conidial head. *Conidiogenous cells* hyaline, terminal, cylindrical, percurrent proliferation, 15-37 x 5-7 μm. *Conidia* hyaline, solitary, ellipsoidal, guttulate, aseptate, thick walled, 7-25 x 4-6 μm.
Habitat: Mushroom compost, straw bedding used for pigs, horse dung and soil.
Distribution: USA, UK and India.
Description: Based on our isolate IMI 364224.

Thermomyces ibadanensis Apinis and Eggins (1966)

Colonies on malt extract agar velvety gray-green, spreading with a narrow, colourless to green marginal zone. Hyphae hyaline, septate, branched, 2-3 μm in diameter. *Conidiophores* short, formed as simple or branched, clustered, more or less cylindrical or spindle shaped side branches of the main hyphae, 6-14 μm long and 1.5-3 μm wide, cut off from the main hyphae by septa at their base, tip narrow bearing a single conidium. *Conidia* hyaline at first, later turning brown, single celled, smooth, thick walled, about 4-8 μm in diameter with a single cylindrical, stalk like appendage 1.5-8 x 1.5-2.5 μm.
Habitat: Oil palm kernel stacks and soil.
Distribution: Nigeria and India.
Description: Based on Apinis and Eggins (1966).

Thermomyces lanuginosus Tsiklinskya (1899)
Syn.: = *Humicola lanuginosa* Griffon and Maublanc (1911)

= *Sepedonium lanuginosum* (Miehe) Griffon and Maublanc (1911)
= *Monotospora lanuginosa* (Griffon and Maublanc) Mason (1933)
= *Acremoniella* sp. Rege(1927) Mason (1933)
= *A. thermophila* Curzi (1930) Mason (1933)

Colonies on YpSs at 45^{o}C appear white at first, but soon turn gray, beginning at the center of the colony. Gradually the colony turns purple brown, the agar stains deep pink or wine colour due to the secretion of diffusible substances. Mature colonies appear dull dark brown to black. *Hyphae* colourless, septate, 1.5-4 μm in diameter. *Conidiogenous cell* arise at right angle to the hyphae, 10-15 μm long, generally unbranched or rarely branched once or twice near the base forming clusters, often septate. *Conidia* single on each conidiogenous cell, colourless, spherical, smooth walled when young, at maturity turn dark brown and sculptured, 6-10 μm in diameter, separating easily from the conidiogenous cell and commonly retain a short attachment piece.
Habitat: Soil, moist oats, cereal grains, coal mine soils, coal spoil tips, mushroom compost, guayule rets, hay, manure, leaf mold peat, garden compost, horse, sheep and pig dung, cow, air and various plant substances.
Distribution: USA, UK, Nigeria, Ghana, India, Japan, Australia and Indonesia.
Description: Based on our isolates IMI 361366, 361369.

Discussion

As discussed in the preceding section, thermophilic fungi form a small physiologically distinct group of about forty species. Growth of these fungi at high temperature is a rare feature. The first thermophilic fungus, *Mucor pusillus*, was isolated from bread and described by Lindt (1886) over a century ago. Tsiklinskaya discovered another thermophilic fungus, *Thermomyces lanuginosus* in (1899) from potato inoculated with garden soil. Miehe (1907) investigated the cause of thermogenesis of stored agricultural produce. He reported four thermophilic fungi viz., *Mucor pusillus*, *Thermoascus aurantiacus*, *Thermoidium sulfureum* and *Thermomyces lanuginosus* from self-heating hay. Miehe, who explained the self-heating of hay and other plant materials was the first person to work extensively on thermophilic fungi. Following the work of Miehe, thermophilic fungi were isolated from various natural substrates (Noac, 1912; Allen, 1950). Cooney and Emerson (1964) for the first time presented a comprehensive account of thermophilc fungi in which they provided taxonomic descriptions of 13 species of thermophilc fungi

known till that time. This monograph, in English, for the first time was a gateway for the mycologist to search for this unusual group of fungi. Since then, several of these fungi have been described. Mouchacca (1997) reviewed the taxonomic status of thermophilic fungi. In this review, we have attempted to provide the detailed taxonomic descriptions, a simplified key to their identification and the natural habitats of known therophilic fungi. We have also tried to include the frequently available data on the distribution of these fungi.

While reviewing the literature, we faced difficulties on account of confusion created by several investigators regarding thermophily. One such example is that of Crisan (1973) who presented a list of 55 thermophilous fungi, however, only half of these are thermophiles in the sense of Cooney & Emerson (1964). Further, difficulties in defining true thermophiles emanates from the absence of reliable growth data covering a wide range of temperatures for most taxa proposed as thermophiles. Thus, such data is needed to ascertain the true nature of few members of this physiologically distinct group of fungi.

The ability of thermophilic fungi to develop at high temperature is depicted by a few Zygomycetes, and several Ascomycetes and Deuteromycetes (Hyphomycetes). No Basidiomycetes was found to be thermophilic. Five thermophilic Zygomycetous fungi discussed in this paper comprise the monospecific *Absidia corymbifera* and several *Rhizomucor* and *Rhizopus* species. Further, as reported by Mouchacca (1997) the validity of *Rhizomucor tauricus* and *R. nainitalensis* is questioned. Similarly confusion exist regarding the designation of *A. corymbifera* as a true thermophilic fungus.

The thermophilic ascomycetous fungi comprise a group of twenty-three species belonging to nine genera. Following Hawksworth *et al*. (1995) *Thermoascus* and *Talaromyces* belong to the family Trichocomaceae, order Eurotiales. The remaining genera are representatives of families Chaetomiaceae (*Chaetomium* and *Thielavia*), Ceratostomatatceae (*Corynascus*), Familiae incertae sedis (*Melanocarpus*) and Microascaceae (*Canariomyces*) of the order Sordariales. *Dactylomyces, Thermoascus* and *Canariomyces* appears monospecific as far as thermophily is concerned. *Talaromyces* has four species. Five species and two varieties in the present paper represent *Chaetomium*. Most but not all thermophilic ascomycetes have conidial anamorphic state. Species belonging to *Chaetomium* do not develop conidia of any kind and thus do not possess anamorphic state. Species belonging to *Thermoascus* regularly produce conidia and our own culture of *Thermoascus* produced catenate condia and can be regarded as anamorphic having *Polypaecilum* stage. For the time being, we have retained *Thermoascus* representing one species. The genus *Coonemeria* is still a matter of debate as stressed by Mouchacca (1997). The genus *Talaromyces* has *Penicillium*

anamorphic stage. Regarding the genus *Thielavia*, *T. pingtungia* has no conidial state, a feature characteristic of all known Chaetomia. *T. australiensis* was reported to have an anamorphic state of the *Trichosporiella*. *Thielavia terricola* is associated with *Acremonium alabamensis*, a distinctive anamorphic state of the teleomorph. The anamorphs of several species of *Corynascus* (Arx, 1975) are placed in *Myceliophthora* (Oorschot, 1977, 1980). This genus is appropriate for disposition of cellulosic sordariaceous anamorphs in which solitary conidia (aleurioconidia) are borne on swollen cells or are sessile.

The Deuteromycetes (Anamorphic fungi) comprises fourteen species belonging to nine genera: *Acremonium*, *Arthrinium*, *Papulospora*, *Remersonia*, *Malbranchea*, *Chrysosporium*, *Myceliophthora*, *Scytalidium* and *Thermomyces.* The imperfect state of *Corynascus thermophilus* is *Myceliophthora fergusii* and it should not be confused with the teleomorph of *M. thermophila*. *Malbranchea cinnamomea* is the only species of *Malbranchea* with thermophilic nature, other species of this genus are mesophiles. *Scytalidium thermophilum* is a synonym of *Torula thermophila*, which is frequently reported from composts. *Acremonium albamensis* is reported to be the imperfect state of *Thielavia terricola*. The taxonomic status of *Thermomyces lanuginosus* as the first assessed thermophilic fungus is supported by majority of the investigators. Its nomenclatural history involved genera as *Acremoniella*, *Humicola*, *Monotospora* and *Sepedonium.* The name *Remersonia thermophila* has been proposed for *Stilbella* as the later had an uncertain position and required a more appropriate genus Seifert *et al.* (1997).

As suggested by Mouchacca (1997) strict restriction to nomenclatural rules governing citations of fungal binomials is fundamental. Many researchers use their own strains for the production of metabolites, this is of course, welcome as some strains of related isolates are highly productive. Therefore, the authors of applied research dealing with thermophiles should necessarily follow such regulations in order to stabilize names of strains used for applied research or in produced goods. This will definitely bring an end to the chaotic state prevailing especially in publications relating to fungal taxonomy and biotechnology.

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References

Abdullah, S.K., Zora, S.E. (1993) *Chaetomium mesopotamicum* a new thermophilic species from Iraqi soil. Cryptogamic Botany 3 (4): 387-389.

Ames, L.M. (1963) A monograph of the Chaetomiaceae. U.S. Army Research and Development series 2, Bibliotheca Mycologica Cramer, Lehre.
Apinis, A.E. (1963) Occurrence of thermophilic fungi in certain alluvial soils near Nottingham. Nova Hedwigia 5: 57-78.
Apinis, A.E. (1967) *Dactylomyces* and *Thermoascus*. Transactions of British Mycological Society 50: 573-582.
Apinis, A.E. and Chesters, C.G.C. (1964) Ascomycetes of some salt marshes and sand dunes. Transactions of British Mycological Society 47: 419-435.
Apinis, A.E. and Eggins, H.O.W. (1966) *Thermomyces ibadanensis* sp.nov. from oil palm kernel stacks in Nigeria. Transactions of British Mycological Society 49: 629-632.
Arx J.A. von, Figueras, M.J. and Guarro, J. (1988) Sordariaceous ascomycetes without ascospore ejaculation. Beihefte zur nova hedwigia 94: 1-104.
Arx, J.A. von (1975) On *Thielavia* and some similar genera of ascomycetes. Studies in Mycology No. 8 CBS Baarn, Netherlands.
Arx, J.A. von (1981) - On *Monilia sitophila* and some families of Ascomycetes. Sydowia 34: 12-29.
Arx, J.A. von (1981a) The genera of fungi sporulating in pure culture. Lubrecht & Cramer Ltd.
Austwick, P.K.C. (1976) Environmental aspects of *Mortierella wolfii* infection in cattle. Newzealand Journal of Agricultural Research 19: 25-33.
Awao, T. and Otsuka, S. (1974) Notes on thermophilic fungi in Japan. Transactions of the mycological society of Japan 15: 7-22.
Awao, T. and Udagawa, S.I. (1983) A new thermophilic species of *Myceliophthora*. Mycotaxon 16(2): 436-440.
Basu, M. (1984) *Myceliophthora indica* is a new thermophilic species from India. Nova hedwigia 40: 85-90.
Bunce, M.E. (1961) *Humicola stellatus* sp.nov., a thermophilic mould from hay. Transactions of British Mycological Society 44: 372-376.
Carmichael, J.W. (1962) *Chrysosporium* and some other aleurosporic hyphomycetes. Canadian Journal of Botany 40: 1137-1174.
Chen, K.Y. and Chen, Z.C. (1996) A new species of *Thermoascus* with a *Paecilomyces* anamorph and other thermophilic species from Taiwan. Mycotaxon 50: 225-240.
Cole, G.T. and Samson, R.A. (1979) *Patterns of Development in Conidial Fungi*. Pitman, London.
Cooney, D.G. and Emerson, R. (1964). *Thermophilic Fungi – an account of their biology, activities and classification.* W.H. Freeman and Co., San Francisco.
Crisan, E.V. (1973) Current concept of thermophilism and thermophilic fungi. Mycologia 65: 1171-1198.
Ellis, D.H. (1982) Ultrastructure of thermophilic fungi V. Conidial ontogeny in *Humicola grisea* var. *thermoidea* and *H. insolens*. Transactions of the British Mycological Society 78: 129-139.
Emmons, C.W. (1930) *Coniothyrium terricola* proves to be a species of *Thielavia*. Bulletin of Torrey Botanical Club 57: 123-126.
Emmons, C.W. (1932) The development of the ascocarp in two species of *Thielavia*. Bulletin of Torrey Botanical Club 59: 415-420.
Fergus, C.L. (1964) Thermophilic and therotolerant molds and actinomycetes of mushroom compost during peak heating. Mycologia 56: 267-283.
Fergus, C.L. (1971) The temperature relationships and thermal resistance of a new thermophile *Papulaspora* from mushroom compost. Mycologia 63: 426-431.
Fergus, C.L. and Sinden, J.W. (1969) A new thermophilic fungus from mushroom compost: *Thielavia thermophila* spec. nov. Canadian Journal of Botany 47: 1635-1637.
Gams, W. and Lacey (1972) *Acremonium thermophilum*. Transactions of the British mycological Society 59: 520.
Griffon, E. and Maublanc, A. (1911) Deux moisissures thermophiles. Bulletin of the Society of Mycology, France 27: 68-74.

Guarro, J., Abdullah, S.K., Al-Bader, S.M., Figueras, M.J. & Gene, J. (1996) The genus *Melanocarpus*. Mycological Research 100: 75-78.
Hawksworth, D.L., Kirk, P.M., Sutton, B.C. and Pegler, D.N. (1995) *Ainsworth and Bisby's Dictionary of Fungi* 8th Edition. International Mycological Institute, CAB Internationa, UK.
Hedger, J.N., Samson, R.A. and Basuki, T. (1982) *Scytalidium indonesicum.* Transactions of the British mycological Society 78: 365.
Johri, B.N. Satanarayana, T. and Olsen, J. (1999) *Thermophilic Moulds in Biotechnology*. Kluwer Academic Publishers, Dordrecht, Boston, London.
Joshi, M.C. (1982) A new species of *Rhizomucor*. Sydowia 35: 100-103.
Kendrick, W.B. (1971) *Taxonomy of Fungi Imperfecti*. University of Toronto Press, Toronto.
Klopotek, A. vans (1974b) *Thielavia heterothallica spec. nov*., die perfekte form von *Chrysosporium thermophilum.* Archives of microbiology 107: 223-224.
Lendner, A. (1908) Les Mucorinees de la Suisse. Mater. Flore Crypt. Suisse 3: 1-177.
Lindt, W. (1886) Mitteilungen uber einige neue pathogene Schimmelpilze. Arch. Exp. Path. Pharmakol. 21: 269-298.
Lucet, A. and Costantin, J. (1901) Contribution a l'etude des Mucorinees pathogene. Archs Parasit 4: 362-408.
Mahajan. M.K., Johri, B.N. and Gupta, R.K. (1986) Influence of desiccation stress in a xerophilic thermophile *Humicola* sp. Current Science 55: 928-930.
Maheshwari, R., Kamalam, P.T. and Balasubramanyam, D.V. (1987). The biogeography of thermophilic fungi. Current Science 56: 151-155.
Malloch, D. and Cain, R.F. (1972) The Trichocomataceae: Ascomycetes with *Aspergillus*, *Paecilomyces*, and *Penicillium* Imperfect states. Canadian Journal of Botany 50: 2613-2628.
Malloch, D. and Cain, R.F. (1973) The genus *Thielavia*. Mycologia 65: 1055-1077.
Mason, E.W. (1933) Annotated account of fungi received at the Imperial Mycological Institute. List II (Fascicle 2), Imperial Mycological Institute, Kew.
Miehe, H. (1907) Die Selbsterhitzung des Heus. Eine. Biologische studie.1-127. Gustav Fischer, Jene.
Morgan-Jones, G. (1974) Notes on Hyphomycetes-V. A new thermophilic species of *Acremonium.* Canadian Journal of Botany 52: 429-431.
Mouchacca, J. (1997) Thermophilic fungi: Biodiversity and Taxonomic Status. Cryptogamie Mycologie 18(11): 19-69.
Mouchacca, J. (2000) Thermophilic fungi and applied research: a synopsis of name changes and synonymies. World Journal of Microbiology & Biotechnology 16: 881-888.
Narain, R., Srivastava, R.B. and Mehrotra, B.S. (1983) A new thermophilic species of *Scytalidium* from India. Zentralblatt für mikrobiologie 138: 569-572.
Naumov, N.A. (1935) Opredelitel' Mukorovykh (Mucorales), Moscow.
Noack, K. (1912) Beiträge zur Biologie der thermophilen Organismen. Jahrbücher für wissenschaftliche Botanik 51: 593-648.
Oorschot, C.A.N. van (1977) The genus *Myceliophthora*. Persoonia 9: 404-408.
Oorschot, C.A.N. van (1980) A revision of *Chrysosporium* and allied genera. Studies in mycology 20: 1-89.
Oorschot, C.A.N. van and Hoog, G.S. de (1984) Some hyphomycetes with thallic conidia. Mycotaxon 20: 129-132.
Pitt, J.I. (1979) *The genus Penicillium and its teleomorphic states Eupenicillium and Talaromyces.* Academic Press, London.
Raper, K.B. and Thom, C. (1949). *A Manual of Penicillia*. Williams and Wilkins Co., Baltimore.
Satyanarayana, T. and Johri, B.N. (1984) Thermophilic fungi of paddy straw compost: growth, nutrition and temperature relationships. Journal of Indian Botanical Society 63: 164-170.
Schipper, M.A.A. (1978) On the genera *Rhizomucor* and *Parasitella*. Studies in Mycology 17: 53-71.

Seifert, K.A., Samson, R.A., Boekhout, T. and Louis-Seize, G. (1997) *Remersonia*, a new genus for *Stilbella thermophila*, a thermophilic mould from compost. Canadian Journal of Botany 75: 1158-1165.
Sigler, L. and Carmichael, J.W. (1976) Taxonomy of *Malbranchea* and some other hyphomycetes with arthroconidia. Mycotaxon 4: 349-488.
Sopp, J.O. (1912) *Monographie der Pilzgruppe Penicillium mit besonderer Berücksichtigung der in Norwegen gefundenen Arten.* Videnskabs-Selskabets i Christiania, Skrifter, 1 Math.-Naturv. Kl., 1912, N° 11, i-vi + 208 pp.
Stolk, A.C. (1965) Thermophilic species of *Talaromyces* Benjamin and *Thermoascus* Miehe. Antonie van Leeuwenhoek 31: 262-276.
Stolk, A.C. and Samson, R.A. (1972) The genus *Talaromyces*- studies on *Talaromyces* and related genera - II. Studies in mycology 2: 1-65.
Tansey, M.R. and Brock, T.D. (1972) The upper temperature limit for eukaryotic organisms. Proceedings of national Academy of Sciences 69: 2426-2428.
Tansey, M.R. and Jack, M.A. (1975) *Thielavia australiensis* sp.nov., a new thermophilic fungus from incubator bird (mallee fowl) nesting material. Canadian Journal of Botany 53: 81-83.
Thakre, R.P. and Johri, B.N. (1976). Occurrence of thermophilic fungi in coal-mine soils of Madhya Pradesh. Current Science 45: 271-273.
Tsiklinskaya, P. (1899) Sur les mucedinees thermophiles. Ann. Inst. Pasteur, Paris 13: 500-505.
Tubaki, K., Ito, T. and Natsuda, Y. (1974) Aquatic sedement as a habitat of thermophilic fungi. Annals of Microbiology 24: 199-207.
Ueda, S. and Udagawa, S.I. (1983) *Thermoascus aegyptiacus*, a new thermophilic ascomycete. Transactions of the Mycological Society of Japan 24: 135-142.

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