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Notes on phytopathogenic fungi reported from Sikkim, India and their broad inter-taxa affinities to plant hosts as inferred from data mining

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Abstract

Fungi play a critical role in plant pathology, and impact human economy and food security. This study focuses on compiling a checklist of phytopathogenic fungi and their plant hosts reported from Sikkim, India and examines the association between those fungi and plant hosts through Cramer's V test and *dplyr* based data mining in R program with the aim to aid in disease management. The study compiled a checklist of 90 phytopathogenic fungal species under 23 orders, 38 families and 60 genera and 82 species of plant hosts under 38 families and 68 genera and found significant affinities ($p < 0.05$) between fungal taxa and host families. However, associations between fungal taxa with host species was not significant. Jaccard Index of Similarity showed preference towards host family was most common (0.11) between Ascomycota and Basidiomycota, while preference towards host genus was least common (0.00) between Basidiomycota and Oomycota. The study emphasizes the potential of data mining as a tool for identifying patterns of association between phytopathogenic fungi and their plant hosts, identifying alternative hosts, and the significance of phytopathogenic fungi as a source of bioactive compounds like antibiotics and enzymes, as well as their potential to produce mycotoxins and allergenic contaminants that pose a threat to human health. The study suggests further evaluation of the role of endophytes and saprophytes (facultative parasites) in disease development, documentation of disease incidence locations, and identification of fungal phytopathogens at the strain, pathotype, or forma specialis level towards effective disease monitoring and management.

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Introduction

Fungi are an indispensable part of an ecosystem and represent the second largest biotic group in nature. However, while they are a source of various enzymes and antibiotics beneficial to humans, fungal plant pathogens are also important negative factors that affect food security, health and economy[1,2]. In fact, plant diseases cause an annual estimated loss of 10%–15% of the world's major crops, with direct economic losses of billions of dollars, and 70%–80% of these diseases are caused by pathogenic fungi[3]. These diseases have had a significant impact on economy and food security in the past, as evidenced by the late blight of potato caused by *Phytophthora infestans*, wheat stem rust caused by *Puccinia graminis*, Asian soybean rust caused by *Phakopsora pachyrhizi*, rice blast caused by *Magnaporthe oryzae*, and banana black sigatoka caused by *Mycosphaerella fijiensis*[4].

Sikkim, nestled in the Eastern Himalayas, is a unique and culturally rich landscape that is endowed with rich floral and faunal diversity[5]. While explorations to date has led to the current understanding of the state's bioresources[5], including macrofungi[6−8], little is known about the regional phytopathogenic fungi. A species checklist of phytopathogenic fungi is an important baseline for the understanding of pathogen-host affinities, pathogen invasion and dominance, and is hence helpful for managing plant diseases[9]. As Sikkim is the world's first all-organic state[10], knowledge of the regional phytopathogenic fungi is crucial for supporting decisions on sustainable agriculture practices. Such a checklist, when coupled with associated species, genus and family of the host provide important insight into the range of alternate and alternative (collateral) host of the phytopathogenic fungi, which would aid in their integrated management[3].

Data mining is the process of extraction of patterns representing knowledge implicitly stored or captured in databases or other information repositories and data streams[11]. Tabulated species checklists are a type of non-parametric categorical (nominal) data, that can be analysed using various statistical tests such as the McNemar test, Cochran Q test, Chi-Square test, and Fisher's Exact test. Nominal associations or affinities can be calculated using coefficients that measure the strength of a relationship between two variables[11].

Among the chi-square-based measures of nominal association, Cramer's V is the most commonly used. Cramer's V normalizes the output from 0 to 1 regardless of table size, especially when row and column marginals are equal, making it a useful measure for assessing associations between two variables expressed as a percentage of their maximum possible variation. Cramer's V is calculated as the square root of chi-square divided by sample size (n), times (m), which is the smaller of (rows - 1) or (columns - 1): $V = SQRT(\chi^2/nm)$[12].

In the current study, the phytopathogenic fungi reported from Sikkim, India is compiled and broad inter-taxa affinities (associations) were studied among the fungal pathogens and their hosts using data mining based on the checklist.

Materials and methods

Initially, publications on microfungi reported from Sikkim, India were surveyed, with a focus on the terms such as 'plant disease', 'upon', 'on', and 'substrate/host'. The pathogenic nature and other life modes of individual fungal entities were then corroborated based on available literature, and any errors or inconsistencies in the checklist were corrected. Fungal species names were verified with their currently accepted names using mycobank.com and indexfungorum.org, author names of fungal genus and the corresponding family were verified from outlineoffungi.org, and reported host names were confirmed using worldfloraonline.org (formerly theplantlist.com). The resulting checklist was sorted into various column heads, namely fungal phylum, order, family, genus, and species, as well as plant host genus and family, using MS Excel 2019.

The process of data cleaning was conducted in four stages. Firstly, reports of the fungal species and the host species/genus that had not been mentioned in mycobank.com and indexfungorum.org websites, as well as worldfloraonline.org, respectively, were separated. Secondly, species with incertae sedis status for both their family and order were removed. Thirdly, if a species was reported from the same host species, only one record was retained. Lastly, fungi ascribed as hyper-parasites, entomogenous, sooty molds, and saprobes were filtered from pathogenic fungi. The resulting cleaned datasheet was then imported in the R programming environment[13], and Pearson's Chi-squared Test based Cramer's V analysis was performed using the *assocstats* function of *vcd* Package[14]. This analysis was based on contingency tables between pathogen-related character vectors such as phylum, order, family, genus, species, and the corresponding plant host species, genus and family. Extraction and summarization of tabular data were conducted using *dplyr* package[15]. The Jaccard index of similarity among host-related character vectors in the phyla Ascomycota, Basidiomycota and Oomycota were obtained using *jaccardSets* function of *bayesbio* package[16].

Results and discussion

In the current study, the exploration of the relevant literature has resulted in the reporting of 90 species of plant pathogenic fungi under 60 genera belonging to 38 families (including incertae sedis) and 23 orders from the state of Sikkim, India. According to the results, the Ascomycota was the most diverse group represented by 16 orders, 26 families, 46 genera and 70 species, followed by Basidiomycota which was represented by six orders, 10 families, 12 genera and 13 species. However, Oomycota was represented by two number of orders, families, genera and seven species respectively (Fig. 1; Table 1). The diversity of hosts were represented by a total of 38 families, 68 genera and 82 species (Fig. 2; Table 1). A checklist of phytopathogenic fungi from Sikkim and reported hosts are presented in Table 1.

Species of Ascomycota with currently undefined order and family

The species which belonged to Ascomycota but which are not currently affiliated to any order or family (incertae sedis) were corroborated with mycobank.com and indexfungorum.org and noted as follows. *Ceratocladium microspermum* Corda saprobic on dead leaves and culms of *Dendrocalamus* sp.

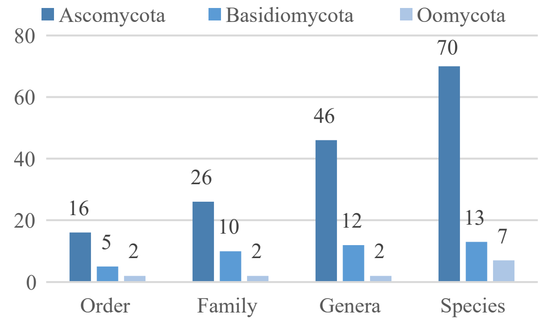

Fig. 1 Numeric distribution of fungal phylum in order, family, genera and species of phytopathogenic fungi.

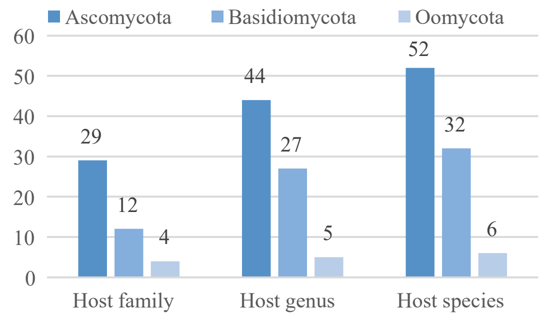

Fig. 2 Numeric distribution of fungal phylum of phytopathogenic fungi in family, genera and species of the plant hosts of Sikkim, India.

(Poaceae), in Sikkim[142]; *Didymosporium culmigenum* Sacc. on leaves & culms of grass probably of *Saccharum* sp. (Poaceae), in Gangtok, Sikkim[143]; *D. culmigenum* on leaves & culms of grass probably of *Saccharum* sp. (Poaceae), in Gangtok, Sikkim[144]; *Phaeodactylium alpiniae* (Sawada) M.B. Ellis. causing leaf spot on *Curcuma longa* L. (Zingiberaceae), in Shilong, Sikkim[145]; *Plenotrichum castanopsidis* J.N. Kapoor & Munjal on leaves of *Castanopsis tribuloides* A.DC. (Fagaceae), in Sikkim[146]; *Phragmocephala elliptica* (Berk. & Broome) S. Hughes (reported as *Endophragmia elliptica* (Berk & Broome) M.B. Ellis saprobic upon decaying herbaceous stem, in Sikkim[142]; *Septogloeum bullatum* Syd. & P. Syd. (reported as *Phloeospora bullata* (Syd. & P. Syd.) B. Sutton; Mycosphaerellaceae, Mycosphaerellales) on saprobic on dried twigs & branches of *Bambusa tulda* Roxb. (Poaceae), in Gangtok, Sikkim[25].

Erroneous reports

The host of *Didymella exigua* (Niessl) Sacc. (Ascomycota, Pleosporales, Didymellaceae) has been reported[31] as *Clerodendon*, but there is no such host genus. *Oronaria babusae* Roxb. has been reported as host of *Corynespora cassiicola* (Berk. & M.A. Curtis) C.T. Wei. (Ascomycota, Pleosporales, Corynesporaceae) and *Cercospora menthicola* Tehon & E.Y. Daniels (Ascomycota, Mycosphaerellales, Mycosphaerellaceae)[36], but there is no such host species. *Paradoxa bimornica* Sw. has been reported as host of *Memnoniella echinata* (Rivolta) Galloway (Ascomycota, Hypocreales, Stachybotryaceae)[36], but there is no such host species. *Prunus communis* L. has been reported as host of *Pestalosphaeria elaeidis* (C. Booth & J.S. Robertson) Aa.; Amphisphaeriaceae [current name *Pseudopestalotiopsis elaeidis* (C. Booth & J.S. Robertson) F. Liu, L. Cai & Crous (Ascomycota, Amphisphaeriales, Sporocadaceae)][147], but there is no such host species.

Table 1. Checklist of phytopathogenic fungi from Sikkim, India and reported plant hosts.

Order	Family	Genus	Species	Remarks
Phylum Ascomycota				
Amphisphaeriales	Sporocadaceae Corda	*Pestalotiopsis* Steyaert	*Pestalotiopsis microspora* (Speg.) G.C. Zhao & N. Li (reported as *Pestalotiopsis royenae* (Guba) Steyaert) causing foliar disease on *Amomum subulatum* Roxb. (Zingiberaceae), in Gangtok, Sikkim[17]	*Pestalotiopsis microspora* is an endophytic fungus causing leaf spot disease on crops[18]. Isolates of this fungus are reported to break down and degrade synthetic polymer polyester polyurethane with the enzyme Serine Hydrolase[19].
		Robillarda Sacc.	*Robillarda sessilis* (Sacc.) Sacc. causing leaf spot on *Amomum subulatum* Roxb. (Zingiberaceae) Northern Sikkim[20]	*Robillarda sessilis* is reported from variable hosts and substrates like bark, dead branches, seeds and leaves. It is reported to cause leaf spot disease[21].
Botryosphaeriales	Botryosphaeriaceae Theiss. & H. Syd.	*Diplodia* Fr.	*Diplodia macrostoma* Lév. on cobs of *Zea mays* L. (Poaceae) in Kalimpong, W.B. and Sikkim[22]; *D. macrostoma* on cobs of *Zea mays* L. (Poaceae) in Kalimpong, W.B. and Sikkim[23]	*Diplodia macrostoma* is parasitic causal organism of dry rot of ears and stalks of maize and frequently also associated with leaf lesions of Maize[24].
		Guignardia Viala & Ravaz	*Guignardia bidwellii* (Ellis) Viala & Ravaz on living leaves of *Asplenium nidus* L. (Aspleniaceae), in Gangtok, Sikkim[25]	It is a hemibiotrophic fungus[26].
		Macrophomina Petr.	*Macrophomina phaseolina* (Tassi) Goid. causing leaf spot on *Schima wallichii* (DC.) Choisy (Theaceae), in Sikkim[27]	It is a generalist soil borne pathogen present worldwide, affecting around 500 species of plants belonging to more than 100 families. It causes stem and root rot, charcoal rot and seedling blight[28].
		Neofusicoccum Crous, Slippers & A.J.L. Phillips	*Neofusicoccum ribis* (Slippers, Crous & M.J. Wingf.) Crous, Slippers & A.J.L. Phillips (reported as *Botryosphaeria ribis* Grossenb. & Duggar) causing leaf spot on *Quercus acutissima* Carruth. (Fagaceae), in Gangtok, Sikkim[29]	It is identified as a pathogen on numerous woody host plants worldwide[30].
	Phyllostictaceae Fr.	*Phyllosticta* Pers.	*Phyllosticta sorghina* Sacc. (reported as *Phoma sorghina* (Sacc.) Boerema, Dorenb. & Kesteren [Pleosporales, Didymellaceae]) on leaves of *Thysanolaena latifolia* Honda; Poaceae (reported as *Thysanolaena Agrostis* Nees), in Gangtok, Sikkim[31]	It is a widely distributed grain mold, known to produce tenuazonic acid and may be responsible for the human disorder Onyalai, prevalent in Africa which is diagnosed by haemorrhagic vesicles in the mouth that appear after the ingestion of infected Sorghum grains[32].
Chaetomellales	Chaetomellaceae Baral, P.R. Johnst. & Rossman	*Chaetomella* Fuckel	*Chaetomella furcata* Cooke & Massee upon unknown coriaceous leaf, in Sikkim[33]	Species of *Chaetomella* are plant pathogenic fungi producing blackish pycnidia on hosts[34].
Cladosporiales	Cladosporiaceae Chalm. & R.G. Archibald	*Cladosporium* Link	*Cladosporium cladosporioides* (Fresen) G.A. de Vries on leaves of *Coix lacryma-jobi* L. (Poaceae), in Gangtok, Sikkim[35] *Cladosporium herbarum* (Pers.) Link. on living leaves of *Bougainvillea spectabilis* Willd. (Nyctaginaceae) in Ranipul (mentioned as Ranipur), Sikkim[36]	*Cladosporium herbarum* and *C. cladosporioides* are xerophilic species which cause *Cladosporium* rot in grape vines[37] and are also among the most frequently encountered fungi in both outdoor and indoor environments as contaminants occasionally linked to human health problems[38].
Diaporthales	Diaporthaceae Höhn. ex Wehm.	*Stenocarpella* Syd. & P. Syd.	*Stenocarpella macrospora* (Earle) B. Sutton causing zonate leaf spot on *Zea mays* L. (Poaceae), in Sikkim[39]	*Stenocarpella macrospora* is a necrotrophic fungal pathogen of Maize causing Stalk and Ear Rot and Macrospora leaf spot. It also survives saprophytically in maize debris in the form of mycelia and pycnidia, which constitute the main source of primary inoculum[40].
			Stenocarpella maydis (Berk.) B. Sutton (reported as *Diplodia zeae* Lév.) on cobs of *Zea mays* L. (Poaceae) in Chyakung, Sikkim[41]	*Stenocarpella maydis* is associated with Maize and causing white rot of stalk and corn cob. It produces mycotoxins among such as the diploidiatoxin, chaetoglobosins, and diplonine, which causes mycotoxicosis (Diplodiosis), characterized by neurological disorders such as ataxia, paralysis, and liver damage in farm animals fed with infected corn[42].
	Valsaceae Tul. & C. Tul.	*Cryptospora* Tul. & C. Tul.	*Cryptospora caryae* Peck (reported as *Ophiovalsa caryae* (Peck) J.N. Kapoor & S.P. Lal) on stem and twigs of *Juglans regia* L. (Juglandaceae), in Sikkim[43]	*Cryptospora caryae* is endophytic and causes conic erumpent pustulate swellings on surface of host, including *Carya* spp.[44].
Glomerellales	Glomerellaceae Locq. ex Seifert & W. Gams	*Colletotrichum* Corda	*Colletotrichum capsici* (Syd. & P. Syd.) E.J. Butler & Bisby upon *Capsicum annuum* L. and *Capsicum frutescens* L. (Solanaceae) causing Anthracnose[45] *Colletotrichum fructicola* Prihastuti, L. Cai & K.D. Hyde, on *Amomum subulatum* Roxb. (Zingiberaceae), in Sikkim[46] *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. causing anthracnose on *Amomum subulatum* Roxb. (Zingiberaceae), in Sikkim[47]; *C. gloeosporioides* causing leaf spot of wild large Cardamom *Amomum dealbatum* Roxb. (Zingiberaceae), in Sikkim[39]; *C. gloeosporioides* upon *Citrus reticulata* Blanco (Rutaceae) causing Citrus die back disease[45];	*Colletotrichum* spp. are causal organisms for anthracnose/leaf blight disease on diverse plant groups. They are facultative plant pathogen which can live as a saprophyte on dead organic matter or as a pathogen on a host plant[46,50].

(to be continued)

Table 1. (continued)

Order	Family	Genus	Species	Remarks
			C. gloeosporioides (reported as *Glomerella cingulata* (Stoneman) Spauld. & H. Schrenk) causing anthracnose on *F. lacor* Buch.-Ham. / *Ficus tsjakela* Burm.f.; Moraceae (reported as *Ficus infectoria*), in Gangtok, Sikkim[48]; *G. cingulata* causing leaf spot on *Ficus auriculata* Lour. (Moraceae), in Sikkim[49] *Colletotrichum* spp. upon *Phaseolus* spp. (Fabaceae) causing Anthracnose[45]	
Helotiales	Erysiphaceae Tul. & C. Tul.	*Erysiphe* DC.	*Erysiphe polygoni* DC. on living leaves of *Aloe vera* (L.) Burm.f.; Asphodelaceae (reported as *Aloe barbadensis* Mill.), in Gangtok, Sikkim[36]; on *Pisum sativum* L. (Fabaceae) causing powdery mildew	*Erysiphe polygoni* is one of the notorious obligate parasite that invades nearly 300 species of plants[51].
			Erysiphe rhododendri J.N. Kapoor on leaves of *Rhododendron* sp. (Ericaceae), in Sikkim[52]	*Erysiphe rhododendri* along with *E. azaleae*, *E. digitata*, *E. izuensis*, and *E. vaccinii* are important members of the genus *Erysiphe* causing Powdery Mildew in *Rhododendrons*[53].
			Erysiphe sikkimensis Chona, J.N. Kapoor & H.S. Gill on living leaves of *Castanopsis tribuloides* A.DC. (Fagaceae), in Sikkim[54]; *E. sikkimensis* on living leaves of *Castanopsis indica* A.DC. (Fagaceae) in Sikkim[54]	*Erysiphe sikkimensis* is reported to be distributed pan Asia which is specific for *Castanopsis* and *Quercus*[55].
			Erysiphe symploci J.N. Kapoor on leaves of *Symplocos racemosa* Roxb. (Symplocaceae), in Sikkim[52]	Besides *Erysiphe symploci*, *E. nomurae* is another member of *Erysiphe* associated with the genus *Symplocos*[56].
		Oidium Link	*Oidium caesalpiniacearum* Hosag. & U. Barun causing powdery mildew on *Bauhinia purpurea* L. (Fabaceae), in Sikkim[49]	*Oidium* is obligately biotrophic fungi which is considered anamorphic stage of many members of Erysiphales[58].
			Oidium sp. causing powdery mildew on *Alnus nepalensis* D.Don (Betulaceae), in Sikkim[29]	
			Oidium sp. causing aerial blight and collar rot on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]	
	Sclerotiniaceae Whetzel ex Whetzel	*Botrytis* P. Micheli ex Pers.	*Botrytis fabae* Sardiña causing burn boils disease on *Vicia faba* L. (Fabaceae), in Sikkim[39]	It is specific for *Vicia faba*. Despite its pathogenic potential, *Botrytis fabae* is not an obligate parasite, being able to survive saprophytically within diseased plant remains[59].
		Monilinia Honey	*Monilinia urnula* Weinm. (reported as *Sclerotinia urnula* (Weinm.) Rehm) upon mummified fruits of *Vaccinium vacciniaceum* (Roxb.) Sleumer; Ericaceae (reported as *Vaccinium serratum* Wight), in Sikkim[60]	*Monilinia* spp. are reported to be specific on members of Ericaceae, and *M. urnula* along with *M. vaccinii-corymbosi* are notable pathogens of the genus *Vaccinium*[61].
Hypocreales	Incertae Sedis	*Cephalosporium* Corda	*Cephalosporium acremonium* Corda upon *Zea mays* L. (Poaceae), in Kalimpong, Sikkim causing ear rot disease[62]	*Cephalosporium acremonium* is interesting in a sense that it is a saprophyte, and source of the antibiotic Cephalosporin C, as well, it is a human pathogen[63]; it is a hyperparasite upon *Helminthosporium solani* Durieu & Mont.[64]; and a phytopathogen causing black bundle disease of maize[65].
	Nectriaceae Tul. & C. Tul.	*Fusarium* Link	*Fusarium solani* (Mart.) Sacc. upon *Citrus reticulata* Blanco (Rutaceae), in Sikkim[66]	*Fusarium* spp. are also reported to be saprophyte[68]
			Fusarium oxysporum Schltdl upon *Amomum subulatum* Roxb. (Zingiberaceae) causing Rhizome rot; *F. oxysporum* causing Fusarium wilt of *Solanum lycopersicum* L. (Solanaceae); *F. oxysporum* upon *Zingiber officinale* Roscoe (Zingiberaceae) causing Dry rot.[45]	
			Fusarium sp. (*F. moniliforme* J. Sheld./ *F. oxysporum* Schltdl./ *F. solani* (Mart.) Sacc.) causing yellows in *Zingiber officinale* Roscoe (Zingiberaceae), in Sikkim[67]	
Meliolales	Meliolaceae G.W. Martin ex Hansf.	*Meliola* Fr.	*Meliola himalayensis* J.N. Kapoor on *Bridelia montana* Woodrow ex J.J.Sm. (Phyllanthaceae), in Sribadam, West Sikkim[69]	Members of genus *Meliola* are parasitic on vascular plants and causes black mildew disease[70].
			Meliola molleriana G. Winter (reported as *Irenopsis molleriana* (G. Winter) F. Stevens) on *Triumfetta rhomboidea* Jacq. (Malvaceae); (reported as *Triumfetta bartramia* L.), in Sribadham, West Sikkim[69]	
			Meliola ostodis J.N. Kapoor on *Ostodes paniculata* Blume (Euphorbiaceae) at Singhik, North Sikkim[69]	
			Meliola symingtoniae J.N. Kapoor on *Exbucklandia populnea* (R.Br. ex Griff.) R.W.Br.; Hamamelidaceae (reported as *Symingtonia populnea* (R.Br. ex Griff.) Steenis) in West Sikkim[69]	

(to be continued)

Table 1. (continued)

Order	Family	Genus	Species	Remarks
Mycosphaerellales	Mycosphaerellaceae Lindau	*Cercospora* Fresen. ex Fuckel	*Cercospora kikuchii* (T. Matsumoto & Tomoy.) M.W. Gardner, causing aerial blight and collar rot of *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Sikkim[57] *Cercospora menthicola* Tehon & E.Y. Daniels on living leaves of *Wrightia tinctoria* R.Br. (Apocynaceae), Sikkim[36]	*Cercospora* is one of the anamorphs of *Mycosphaerella*, and represent one of the largest group of plant pathogenic obligate parasitic fungi that cause leaf spots[71].
		Mycosphaerella Johanson	*Mycosphaerella aethiops* (Auersw.) Lindau (reported as *Mycosphaerella aethiopes* (Fuckel) Kapoor & Gill) on leaves of *Quercus* sp. (Fagaceae), in Sikkim[72] *Mycosphaerella bolleana* Higg. causing leaf spot and mould on *Terminalia bellirica* (Gaertn.) Roxb. (Combretaceae), in Sikkim[49]	*Mycosphaerella* is a necrotrophic plant pathogen[73].
		Mycovellosiella Rangel	*Mycovellosiella cajani* (Henn.) Rangel ex Trotter causing flowery spot on *Cajanus cajan* (L.) Huth (Fabaceae), in Northern Eastern Hill Region including Sikkim[74]	It is a seed borne pathogen of *Cajanus cajan* causing necrotic spots on leaves[75].
		Passalora Fr.	*Passalora bolleana* (Thüm.) U. Braun (reported as *Cercosporidium bolleanum* (Thüm.) X.J. Liu & Y.L. Guo) causing vein necrosis and leaf spot on *Ficus auriculata* Lour. (Moraceae), in Sikkim[49]; *P. bolleanum* causing leaf spot on *F. lacor* Buch.-Ham. / *Ficus tsjakela* Burm.f.; Moraceae (reported as *Ficus infectoria*), in Sikkim[49]	*Passalora* is one of the anamorphs of *Mycosphaerella*, and it is an obligate plant obligate parasitic fungus that cause leaf blight and leaf spots[71].
		Peyronellaea Goid. ex Togliani	*Peyronellaea pinodes* (Berk. & A. Bloxam) Aveskamp (reported as *Mycosphaerella pinodes* (Berk. & A. Bloxam) Vestergr.) causing aerial blight and collar rot on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]	*Peyronellaea pinodes* is a hemibiotroph causing leaf spot and foot rot of *Pisum sativum*, and is prevalent worldwide[76].
		Pseudocercospora Speg.	*Pseudocercospora macarangae* (Syd. & P.Syd.) Deighton. on leaves of *Macaranga denticulata* Müll.Arg. (Euphorbiaceae), in Gangtok, Sikkim[31] *Pseudocercospora osbeckiae* (Chona, Lall & Munjal) Kamal, M.K. Khan & R.K. Verma (reported as *Cercospora osbeckiae* Chona, Lall & Munjal) on leaves of *Osbeckia stellata* Buch.-Ham. ex Ker Gawl. (Melastomaceae), in Chakking, Sikkim[77] *Pseudocercospora* sp. on leaves of *Boehmeria polystachya* Wedd. (Urticaceae), in Gangtok, Sikkim[31]	*Pseudocercospora* is one of the anamorphs of *Mycosphaerella*, and it is an obligate plant parasitic fungus that cause leaf blight and leaf spots[71].
		Ramularia Unger	*Ramularia phaseoli* (O.A. Drumm.) Deighton (reported as *Mycovellosiella phaseoli* (O.A. Drumm.) Deighton) causing farinose leaf spot on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]	*Ramularia* is obligately biotrophic fungi which is considered one of the anamophic stage of many members of Erysiphales[58].
		Septoria Sacc.	*Septoria lablabina* Sacc. causing leaf spot on *Lablab purpureus* subsp. *purpureus* (L.) Sweet; Fabaceae (reported as *Dolichos lablab* L.), in Sikkim[39]	*Septoria lablabina* is associated with lablab bean as causal organism for the leaf spot disease[78].
Myriangiales	Elsinoaceae Höhn. ex Sacc. & Trotter	*Elsinoe* Racib.	*Elsinoe fici* Boedijn causing leaf spot disease of *F. lacor* Buch.-Ham./*Ficus tsjakela* Burm.f.; Moraceae (reported as *Ficus infectoria*), in Sikkim[27]	*Elsinoe fici* is specific for genus *Ficus* and causes diseases ranging from leaf spot to blisters[79].
Phyllachorales	Phyllachoraceae Theiss. & H. Syd.	*Phyllachora* Nitschke ex Fuckel	*Phyllachora euryae* (Racib.) Arx & E. Müll. causing anthracnose on *Schima wallichii* (DC.) Choisy (Theaceae), in Gangtok, Sikkim[48]	Genus *Phyllachora* consists of many obligate parasites causing tar spot / anthracnose disease on plants. Considered host specific, *P. euryae*, *P. cymbispora*, *P. transiens*, *P. gordoniae* and *P. schimae* are reported from Theaceae. *Phyllachora schimae* is reported from *Schima superba*[80].
			Phyllachora repens (Corda) Sacc. causing leaf tar spot on *F. lacor* Buch.-Ham. / *Ficus tsjakela* Burm.f.; Moraceae (reported as *Ficus infectoria*), in Sikkim[49]	*Phyllachora repens* has also been reported as an obligate parasite on *Ficus religiosa*[81].
Pleosporales	Astrosphaeriellaceae Phook. & K.D. Hyde	*Astrosphaeriella* Syd. & P. Syd.	*Astrosphaeriella fuscomaculans* W. Yamam. upon culms of *Drepanostachyum falcatum* (Nees) Keng f.; Poaceae (reported as *Arundinaria falcata* Nees), in Sikkim[82]	*Astrosphaeriella fuscomaculans* is parasitic and known to cause fuscous speckles or 'speckling' disease of Bamboo[83].
		Astrotheca I. Hino	*Astrotheca nigrocornis* I. Hino on dead culms of *Drepanostachyum falcatum* (Nees) Keng f.; Poaceae (reported as *Arundinaria falcata* Nees), in Sikkim[82]	Members of Astrosphaeriellaceae are reported to be specific on Bamboo, palms and snout grasses and other they are known to be both in parasitic and saprotrophic forms[83].
	Didymellaceae Gruyter, Aveskamp & Verkley	*Didymella* Sacc. ex D. Sacc.	*Didymella curtisii* (Berk.) Qian Chen & L. Cai (reported as *Stagonospora curtisii* (Berk.) Sacc. [Pleosporales, Massarinaceae]) on leaves of *Amaryllis* sp. (Amaryllidaceae), in Eastern Sikkim[84]	*Didymella curtisii* is a worldwide fungal pathogen on various plants of the genera *Amaryllis* L., *Hippeastrum* Herb., *Narcissus* L., etc. under family Amaryllidaceae[85].

(to be continued)

Table 1. (continued)

Order	Family	Genus	Species	Remarks
		Leptosphaerulina McAlpine	*Leptosphaerulina trifolii* (Rostr.) Petr. causing aerial blight and collar rot on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]	Besides being pathogenic upon *Vigna umbellata*, *L. trifolii* is also reported to be a fungal endophyte associated to the phyllosphere of olive cultivars in Alentejo region (south of Portugal)[86].
		Neoascochyta Q. Chen & L. Cai	*Neoascochyta exitialis* (Morini) Qian Chen & L. Cai (reported as *Didymella exitialis* (Morini) E. Müll.) on *Zea mays* L. (Poaceae), in Gangtok, Sikkim[23]	*Neoascochyta exitialis* has been reported to be causal organism of leaf spots on members of Poaceae[87].
		Boeremia Aveskamp, Gruyter & Verkley	*Boeremia exigua* (Desm.) Aveskamp, Gruyter & Verkley (reported as *Phoma exigua* Desm.) causing leaf spot on *Phaseolus vulgaris* L. (Fabaceae), in Gangtok, Sikkim[88]	*Boeremia exigua* is considered a pathogen particularly associated with post-harvest diseases, but also causes leaf spot of *Phaseolus vulgaris*, *Ipomoea batatas* etc.[89].
	Incertae Sedis	*Dactuliophora* C.L. Leakey	*Dactuliophora tarrii* C.L. Leakey. causing aerial blight and collar rot of *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]	Genus *Dactuliophora* comprises of sclerotial fungi parasitic upon sorghum, bulrush millet, cowpeas, French beans and soybeans[90].
	Melanommataceae G. Winter	*Seifertia* Partr. & Morgan-Jones	*Seifertia alpina* (Höhn.) Beenken, Andr. Gross & Queloz (reported as *Antromycopsis alpina* Höhn [Agaricales, Pleurotaceae]), living leaves of *Rhododendron* sp. (Ericaceae), on the way to Sikkim[91]	*Seifertia* is reported to be specific for the genus *Rhododendron*[92]. The report of *Seifertia alpina* from Sikkim is based on samples from living leaves, however, *S. alpina* is a rare species reported from Austrian and Swiss Alps[92], and it is saprotrophic, whereas, *S. azaleae* (Peck) Partr. & Morgan-Jones having worldwide distribution and *S. shangrilaensis* Jin F. Li, Phook. & K.D. Hyde distributed in Yunnan Province, China are Necrotrophic and saprotrophic/necrotrophic respectively.
	Periconiaceae Nann.	*Periconia* Tode	*Periconia digitata* (Cooke) Sacc. on dried twigs of *Bambusa* sp. (Poaceae), in Sikkim[36]	*Periconia digitata* has also been associated as saprophyte[93] as well as a plant pathogen[94].
			Periconia nilagirica Subram. on living leaves of *Ipomoea batatas* (L.) Lam. (Convolvulaceae), in Sikkim[36]	*Periconia nilagirica* is also reported as a saprophyte on dead culms of grass[95].
	Pleosporaceae Nitschke	*Alternaria* Nees	*Alternaria alternata* (Fr.) Keissl. upon living leaves of *Solanum betaceum* Cav.; Solanaceae (reported as *Cyphomandra betacea* (Cav.) Sendtn.), in Sikkim[36]; *A. alternata* on living leaves of *Pteris* sp. (Pteridaceae), in Gangtok, Sikkim[36]; *A. alternata* on living leaves of *Luffa aegyptiaca* Mill. (Cucurbitaceae) in Gangtok, Sikkim[36]; *A. alternata* on living leaves of *Wrightia tinctoria* R.Br. (Apocynaceae) in Sikkim[36]; *A. alternata* causing leaf spot on *Solanum betaceum* Cav.; Solanaceae (reported as *Cyphomandra betacea* (Cav.) Sendtn.), in Sikkim[96]	*Alternaria* spp. including *A. alternata* is generally reported to be saprophytic, however, if it meets weakened host, then parasitic mode is activated[97].
			Alternaria brassicae (Berk.) Sacc. upon *Phaseolus* spp. (Fabaceae) causing Leaf spot disease[45] *Alternaria solani* Sorauer upon *Solanum lycopersicum* L. (Solanaceae) causing Early blight; *A. solani* upon *Solanum tuberosum* L. (Solanaceae) causing Early blight[45]	
		Bipolaris Shoemaker	*Bipolaris urochloae* (V.A. Putterill) Shoemaker, on leaves of *Panicum maximum* Jacq. (Poaceae), in Gangtok, Sikkim[31] *Bipolaris zeicola* (G.L. Stout) Shoemaker (reported as *Helminthosporium carbonum* Ullstrup.; Pleosporales, Massarinaceae) on leaves of *Zea mays* L. (Poaceae), in Sikkim and Delhi[99]	Besides Poaceae, *B. urochloae* is also reported as a pathogen of *Dendrobium* (Orchidaceae)[98]. Members of *Bipolaris* are reported to cause disease in members of Poaceae. *Bipolaris zeicola* has also been reported from Rosaceae and Rubiaceae[100].
		Curvularia Boedijn	*Curvularia eragrostidis* (Henn.) J.A. Mey. on leaves on leaves of *Amomum subulatum* Roxb. (Zingiberaceae), in Sikkim[101] *Curvularia lunata* (Wakker) Boedijn. on living leaves of *Pteris* sp. (Pteridaceae), in Sikkim[36]	*Curvularia eragrostidis* is an endophytic fungus causing late blight disease[101]. Although *Curvularia lunata* is a plant pathogen, which has also been isolated from Human lung biopsy[102].
	Torulaceae Corda	*Torula* Pers.	*Torula herbarum* (Pers.) Link on living leaves of *Grevillea robusta* A.Cunn. ex. R.Br. (Proteaceae), in Sikkim[36]	*Torula herbarum* occurs on plant debris and soil as saprophyte, whereas, it also causes blight disease of *Ziziphus mauritiana*, while *Alnus*, *Aceuthobium*, *Bambusa*, *Carya*, *Impatiens*, *Juncus*, *Mesembryanthemum*, *Pinus*, and *Yucca* are also its hosts[103,104]. Due to abundance of conidia in the air, *T. herbarum* contributes to seasonal fungal allergy in some people[105].
Sordariales	Chaetomiaceae G. Winter	*Dichotomopilus* X. Wei Wang, Samson & Crous	*Dichotomopilus funicola* (Cooke) X. Wei Wang & Samson (reported as *Chaetomium funicola* Cooke) on leaves of *Bambusa bambos* (L.) Voss; Poaceae (reported as *Bambusa indica* André) in Gangtok, Sikkim[35]	*Dichotomopilus funicola* is a common fungus of indoor environment and soil, which is also reported as leaf endophyte on various plants[106].

(to be continued)

Table 1. (continued)

Order	Family	Genus	Species	Remarks
Taphrinales	Taphrinaceae Gäum.	*Taphrina* Fr.	*Taphrina caerulescens* (Desm. & Mont.) Tul. causing leaf blotch on *Quercus acutissima* Carruth. (Fagaceae), in Sikkim[39]	*Taphrina caerulescens* is causative organism of Oak leaf blister, with both saprophytic and parasitic stages[107].
Venturiales	Venturiaceae E. Müll. & Arx ex M.E. Barr	*Acantharia* Theiss. & Syd.	*Acantharia elegans* (Syd. & P.Syd.) Arx. on *Quercus* sp. (Fagaceae), in Sikkim[108]; *A. elegans* (Syd. & P.Syd) Arx. (reported as *Lasiobotrys elegans* (Syd. & P.Syd.) Theiss.) on *Quercus* sp. (Fagaceae), in Sikkim[108]	Members of genus *Acantharia* consists of folicolous parasites/ saprophytes[109].
		Venturia Sacc.	*Venturia inaequalis* (Cooke) G. Winter causing apple scab on Apple (*Malus sikkimensis* (Wenz.) Koehne ex C.K.Schneid. (Rosaceae)), in Sikkim[110]	*Venturia inaequalis* is apple scab fungus that has been associated with members of Rosaceae such as crabapples and apples (*Malus* spp.), mountain ash (*Sorbus* spp.), pear (*Pyrus communis*) and Cotoneaster (*Cotoneaster* spp.). It has several host-specific strains that are reported to cause disease on one type of plant but not any other[109, 111].
Phylum Basidiomycota				
Atheliales	Atheliaceae Jülich	*Athelia* Pers.	*Athelia rolfsii* (Curzi) C.C. Tu & Kimbr. (reported as *Sclerotium rolfsii* Sacc. [Typhulaceae, Thelephorales, Basidiomycota]) causing wilt of *Aerides* sp. (Orchidaceae), in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing wilt of *Cattleya* sp. (Orchidaceae), in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing wilt of *Dendrobium* sp. (Orchidaceae) in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing wilt of *Eria coronaria* Rchb.f. (Orchidaceae) in Pakyong, Sikkim[112]; *S. rolfsii* causing wilt of *Habenaria* sp. (Orchidaceae) in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing wilt of *Spathoglottis* sp. (Orchidaceae) in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing rot of pseudobulbs & wilt of *Coelogyne corymbosa* Lindl. (Orchidaceae) in Pakyong, Sikkim[112]; *S. rolfsii* Sacc. causing wilt and basal rot on pseudostems of *Vanda coerulea* Griff. ex Lindl. (Orchidaceae), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing basal rot on pseudostems of *Vanda stangeana* Rchb.f. (Orchiaceae), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing wilt of *Acampe praemorsa* (Roxb.) Blatt. & McCann; Orchidaceae (reported as *Acampe papillosa* Lindl.), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing wilt of *Luisia* sp. (Orchidaceae), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing wilt of *Robiquetia spathulata* J.J.Sm. (Orchidaceae), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing wilt of *Vanda tessellata* Hook. ex G.Don; Orchidaceae (reported as *Vanda roxburghii* R.Br.), in Pakyong, Sikkim[113]; *S. rolfsii* Sacc. causing basal rot on pseudobulbs of *Phaius flavus* (Blume) Lindl. (Orchidaceae), in West Bengal, Sikkim[113,114]; *S. rolfsii* Sacc. causing soft rot of *Paphiopedilum venustum* (Wall. ex Sims) Pfitzer (Orchidaceae), in West Bengal, Sikkim[114]	*Athelia rolfsii* is a soil borne facultative plant pathogen which primarily is a saprophyte and overwinters in form of Sclerotia, however, it is pathogenic agent on crops growing on warm soil causing Southern Blight[115].
Cantharellales	Ceratobasidiaceae G.W. Martin	*Rhizoctonia* DC.	*Rhizoctonia solani* J.G. Kühn. upon *Amomum subulatum* Roxb. (Zingiberaceae) causing Rhizome rot[45]; *R. solani* causing root and collar rot on *Brassica rapa* L.; Brassicaceae (reported as *Brassica campestris* var. *sarson* Prain), in Gangtok, Sikkim[116]; *R. solani* causing root and collar rot on *Brassica juncea* (L.) Czern. (*Brassicaceae*), in Gangtok, Sikkim[116]; *R. solani* causing aerial blight on *Macrotyloma uniflorum* (Lam.) Verdc. (Fabaceae), in Sikkim[117]; *R. solani* causing aerial blight on *Vigna mungo* (L.) Hepper; Fabaceae (reported as *Phaseolus mungo* L.), in Sikkim[117]; *R. solani* causing aerial blight on *Phaseolus vulgaris* L. (Fabaceae), in Sikkim[117]; *R. solani* causing aerial blight on *Vigna radiata* (L.) R.Wilczek (Fabaceae), in Sikkim[117]; *R. solani* causing aerial blight and collar rot on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Gangtok, Sikkim[57]; *R. solani* causing aerial blight on *Dahlia* sp. (Asteraceae), in, Sikkim[118]	*Rhizoctonia solani* is a soil borne necrotroph that inflicts damage to members of Amaranthaceae, Asteraceae, Araceae, Brassicaceae, Fabaceae, Linaceae, Malvaceae, Moraceae, Poaceae, Rubiaceae, and Solanaceae[119].
Microbotryales	Microbotryaceae R.T. Moore	*Microbotryum* Lév.	*Microbotryum emodense* (Berk.) M. Piepenbr. (reported as *Liroa emodensis* (Berk.) Cif.) on peduncles, branches and ochrae of *Persicaria chinensis* (L.) H.Gross; Polygonaceae (reported as *Polygonum chinense* L.), in Tonglo, Sikkim, Nangki, East Nepal, Kodaikanal and Ootacammund, T.N. and Mahabaleshwar, M.S.[120]	*Microbotryum* members are well known parasites of eudicotyledonous plants. Species such as *M. saponariae*, *M. dianthorum*, *M. majus*, *M. violaceum*, *M. lychnidis-dioicae* are reported to be anther parasites of Caryophyllaceae. *M. emodense* is reported to be parasitic upon *Persicaria chinensis*[121].

(to be continued)

Table 1. (continued)

Order	Family	Genus	Species	Remarks
Pucciniales	Coleosporiaceae Dietel	*Chrysomyxa* Unger	*Chrysomyxa deformans* (Dietel) Jacz. on *Picea smithiana* Boiss.; Pinaceae (reported as *Picea morinda* Link), in Simla & Dalhausie, H.P., Sikkim[122]	*Chrysomyxa deformans* has been reported as the causal agent for Red Rust of Spruce Fir Trees[123].
		Melampsoropsis (J. Schröt.) Arthur	*Melampsoropsis elaeocarpi* Vatt. & D.K. Agarwal causing brown leafspot of *Elaeocarpus* sp. (Elaeocarpaceae), in Sikkim, India[124]	*Melampsoropsis* is a heteroecious rust fungus with pycnidial stage on *Picea* and uredial and telial stage members of Ericaceae like *Empetrum*, *Pyrola*, *Rhododendron*, *Ledum* and Elaeocarpaceae like *Elaeocarpus*[124]
		Stilbechrysomyxa M.M. Chen	*Stilbechrysomyxa himalensis* (Barclay) M.M. Chen (reported as *Chrysomyxa himalensis* Barclay), on *Rhododendron hodgsonii* Hook.f (Ericaceae), in Sikkim[125]	*Stilbechrysomyxa himalensis* is a heteroecious rust fungus occurring as teleomorph on *Rhododendron* in the Himalayan region of southern Asia and as anamorph on *Picea*[126].
	Incertae sedis (Cronartiaceae Dietel in Index Fungorum and outline of fungi)	*Peridermium* (Link) J.C. Schmidt & Kunze	*Peridermium thomsonii* Berk and Cooke on leaves of *Picea smithiana* Boiss.; Pinaceae (reported as *Picea morinda* Link), in Mahasu, Near Simla, H.P., North West Himalayas, Sikkim, Kulu, H.P.[35,127]	*Peridermium thomsonii* is rust fungus associated with leaves of *Picea smithiana*[128].
	Phakopsoraceae Cummins & Hirats. f.	*Phakopsora* Dietel	*Phakopsora elletariae* (Racib.) Cummins on leaves of *Amomum subulatum* Roxb. (Zingiberaceae), in Sikkim[129]	*Phakopsora elletariae* is an important rust pathogen of *Amomum subulatum* on plantations above 1800 msl[129].
	Pucciniaceae Chevall.	*Puccinia* Pers.	*Puccinia senecionis-scandentis* Lindr. on *Senecio scandens* (L.) Buch.-Ham. (Asteraceae), in Sikkim, Himalayas[62,63][130,131]	*Puccinia senecionis-scandentis* is a rust fungus associated with *Senecio scandens* (MCP 2022)[132].
			Puccinia ustalis Berk. on leaves of *Ranunculus pulchellus* C.A.Mey. (Ranunculaceae), in Momay, Samdong, Sikkim, Himalayas[133]	*Puccinia ustalis* is an obligate plant parasite reported to be specific for the family Ranunculaceae[134].
		Uromyces (Link) Unger	*Uromyces appendiculatus* (Pers.) Link on *Vigna umbellata* (Thunb.) Ohwi & H.Ohashi (Fabaceae), in Sikkim[135]	*Uromyces appendiculatus* is an obligate parasite of *Vigna umbellata* causing Bean Rust disease[136].
	Urediniaceae Link	*Uredo* Pers.	*Uredo panacis* Syd. & P.Syd. on leaves of *Panax pseudoginseng* Wall. (Araliaceae), in Sikkim[137]	*Uredo panacis* causes yellow rust of *Panax pseudoginseng*[138].
Ustilaginales	Ustilaginaceae Tul. & C. Tul.	*Sporisorium* Ehrenb. ex Link	*Sporisorium setaricolum* (Thrium. & Safeeulla) Bag & D.K. Agarwal on ovaries of *Setaria* sp. (Poaceae), in Ranipul, Sikkim[139]	*Sporisorium setaricolum* is a smut fungus associated with ovary of the genus *Setaria*[139].
Phylum Oomycota				
Peronosporales	Peronosporaceae de Bary	*Phytophthora* de Bary	*Phytophthora citrophthora* (R.E. Sm. & E.H. Sm.) Leonian upon *Citrus reticulata* (Rutaceae) causing Gummosis/ Foot rot/ Color rot/ Trunk rot[45]	*Phytophthora* spp. and *Pythium* spp. are water molds and necrotrophic plant pathogens which also has a saprotrophic mode of life[141].
			Phytophthora colocasiae Racib. causing leaf blight of *Colocasia esculenta* (L.) Schott (Araceae), in Sikkim[140]	
			Phytophthora infestans (Mont.) de Bary upon *Solanum lycopersicum* L. (Solanaceae) causing Late blight; *P. infestans* upon *Solanum tuberosum* L.(Solanaceae) causing Late blight[45]	
			Phytophthora palmivora (E.J. Butler) E.J. Butler upon *Citrus reticulata* Blanco (Rutaceae) causing Gummosis/ Foot rot/ Color rot/ Trunk rot[45]	
			Phytophthora nicotianae Breda de Haan (reported as *Phytophthora parasitica* Dastur) upon *Citrus reticulata* Blanco (Rutaceae) causing Gummosis/ Foot rot/ Color rot/ Trunk rot[45]	
Pythiales	Pythiaceae J. Schröt.	*Pythium* Pringsh.	*Pythium aphanidermatum* (Edson) Fitzp. upon *Zingiber officinale* Roscoe (Zingiberaceae) causing Soft rot[45]	
			Pythium vexans de Bary upon *Amomum subulatum* Roxb. (Zingiberaceae) causing Rhizome rot[45]	

Cercospora oxysporum Berk. & Curt, (Ascomycota, Mycosphaerellales, Mycosphaerellaceae) has been reported as the pathogen on cobs of *Amomum subulatum* Roxb. (Zingiberaceae)[36] but there is no record of such fungal species in Mycobank and Index Fungorum. *Gibberella anne* (Schw.) Petch., (Ascomycota, Hypocreales, Nectriaceae) has been reported as the pathogen on cobs of *Zea mays* L. (Poaceae), in Rongali, Sikkim[41], but there is no record of such fungal species in Mycobank and Index Fungorum. *Palwaniella castanopsidis* Kapoor[148], reported from *Castanopsis tribuloides* A.DC. (Fagaceae) has no record in Mycobank and Index Fungorum, not even generic record.

Interesting records of fungal hyperparasites, entomogenous fungi, sooty moulds and saprobe fungi in association with plants of Sikkim

The study revealed records of hyperparasites, which are fungi that parasitize other fungi, from the genera *Trichothyriella*, *Eudarluca*, and *Cephalosporium*. *Trichothyriella quercigena* (Berk. ex Cooke) Theiss., which is the type of species of the monotypic genus *Trichothyriella*, was reported on the leaves of the *Quercus* species in Sikkim[108] and is a hyperparasite on topical folicolous microfungi[149,150]. *Eudarluca caricis* (Fr.) O.E. Erikss. was reported to grow on *Uromyces appendiculatus* (Pers.) Link is a phytopathogen of *Vigna umbellata*, in Sikkim[135] and is a mycoparasite on the rust fungi *Phragmidium*, whereas *Phragmidium* has preference on members of Rosaceae[151]. *Cephalosporium acremonium*, which was reported on *Zea mays* in Sikkim[62], is a hyperparasite on the phytopathogen *Helminthosporium solani* Durieu & Mont.[64].

Aschersonia cubensis Berk. & M.A. Curtis, which was reported on the leaves of *Citrus reticulata* in Gangtok, Sikkim, is an entomogenous fungi that parasitizes the green scale insect pest *Coccus viridis*[152].

It was noted that two species from Capnodiaceae (Capnodiales, Ascomycota) viz. *Leptoxyphium fumago* (Woron.) Crous and *Tripospermum myrti* (Lind) S. Hughes reported from leaves of *Coix lacryma-jobi* L. (Poaceae), in Gangtok, Sikkim[35] and one member of Coccodiniaceae (Chaetothyriales, Ascomycota) viz. *Limacinula butleri* Syd. & P. Syd. reported from *Dendroclamus* sp. (Poaceae), in Soreng, Sikkim[146] were found to be sooty mold fungi. *Tripospermum myrti* along with members of *Leptoxyphium*, and Coccodiniaceae are epiphytic and grow saprobically upon honey dew released by mealy bug infested upon the plant host. In that sense, the fungus is not directly pathogenic upon the host plants but their Sooty Mat upon foliage and stem impedes photosynthesis in hosts leading to reduced growth rate and reduced yield[153–155]. *Leptoxyphium fumago* has also been reported from *Rhododendron arboreum*[156], which may be useful information for its identification and management in *Rhododendron* dominated wildlife sanctuaries of Sikkim.

Memnoniella echinata (Rivolta) Galloway (Stachybotryaceae, Hypocreales, Ascomycota) reported from dried fallen twigs of *Bambusa polymorpha* Munro (Poaceae), in Sikkim[22] was found to be saprobic growing in soil and dead plant materials[157]; however, it is also reported to be a causal agent for pulmonary heterosiderosis in infants, especially living in water damaged buildings[158]

Other observations from data mining

The common representation of order in terms of counts at the level of species of the Ascomycota include Pleosporales (22), Mycosphaerellales (13), Glomerellales (9), Helotiales (9), Hypocreales (6), Botryosphaeriales (5), Meliolales (4) etc. Similarly, the common representation of order in terms of counts at the level of species of the Basidiomycota include Atheliales (15), Cantharellales (9), Pucciniales (8), Chaetomellales, Microbotryales and Ustilaginales (1 each). Oomycota was represented by Peronosporales (6) and Pythiales (2).

Unique representatives of the phylum Ascomycota were members of the plant families Amaryllidaceae, Apocynaceae, Asphodelaceae, Aspleniaceae, Betulaceae, Combretaceae, Convolvulaceae, Cucurbitaceae, Euphorbiaceae, Fagaceae, Hamamelidaceae, Juglandaceae, Malvaceae, Melastomaceae, Moraceae, Nyctaginaceae, Phyllanthaceae, Proteaceae, Pteridaceae, Rosaceae, Symplocaceae, Theaceae, and Urticaceae which were reported exclusively from the phylum Ascomycota. On the other hand, members of the families Araliaceae, Asteraceae, Brassicaceae, Elaeocarpaceae, Orchidaceae, Pinaceae, Polygonaceae and Ranunculaceae were reported exclusively from the phylum Basidiomycota. Furthermore, three phyla showed an affinity with Zingiberaceae, while Ascomycota and Basidiomycota showed affinities with the families Fabaceae, Poaceae, Zingiberaceae and Ericaceae; and Ascomycota and Oomycota showed an affinity with the families Solanaceae and Rutaceae. At the family level, Poaceae and Ericaceae were reported from both Ascomycota and Basidiomycota. However, the genus *Setaria* (Poaceae) and *Rhododendron hodgsonii* Hook.f (Ericaceae) was reported exclusively from Basidiomycota. Similarly, host genera common to both phyla include *Vigna*, *Amomum*, *Rhododendron* and *Phaseolus* (Table 2). Furthermore, three distinctly identified species requiring alternative hosts were *Alternaria alternata* (Fr.) Keissl. recorded from Apocynaceae, Cucurbitaceae, Pteridaceae, and Solanaceae; *Rhizoctonia solani* J.G. Kühn. recorded from Asteraceae, Brassicaceae, Fabaceae, and Zingiberaceae; and *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. recorded from Moraceae, Rutaceae and Zingiberaceae.

Table 2. Taxa of host common to different fungal phylum.

	Asco	Basi	Oomy
Host family			
Fabaceae	12	5	–
Poaceae	12	5	–
Zingiberaceae	9	2	2
Ericaceae	3	1	–
Solanaceae	6	–	2
Rutaceae	2	–	3
Host genus			
Amomum	8	2	1
Vigna	5	3	–
Phaseolus	3	1	–
Rhododendron	2	1	–
Solanum	3	–	2
Citrus	2	–	3
Zingiber	2	–	2
Host species			
Amomum subulatum Roxb.	6	2	1
Vigna umbellata (Thunb.) Ohwi & H.Ohashi	5	1	–
Phaseolus vulgaris L.	1	1	–
Citrus reticulata Blanco	2	–	3
Solanum lycopersicum L.	2	–	1
Zingiber officinale Roscoe	2	–	1
Solanum tuberosum L.	1	–	1

Asco = Ascomycota, Basi = Basidiomycota, Oomy = Oomycota.

Table 3. Cramer's V values in the lower diagonal and corresponding chi-square based p value in the upper diagonal. p < 0.05 are indicated in bold.

	Phylum	Order	Family	Genus	Species	Host species	Host genus	Host family
Phylum		0.00	0.00	0.00	0.00	0.36	0.10	0.00
Order	**0.99**		0.00	0.00	0.00	0.16	0.00	0.00
Family	**0.99**	**1.00**		0.00	0.00	0.17	0.00	0.00
Genus	**1.00**	**1.00**	**1.00**		0.00	0.99	0.06	0.00
Species	**1.00**	**1.00**	**1.00**	**1.00**		1.00	0.01	0.00
Host species	0.82	0.82	0.82	0.79	0.82		0.00	0.00
Host genus	0.79	**0.78**	**0.78**	0.75	0.86	**1.00**		0.00
Host family	**0.75**	**0.66**	**0.64**	**0.76**	**0.94**	**1.00**	**1.00**	

Table 4. Jaccard index of similarity among various fungal phylum pairs.

Phylum pairs	Host species	Host genus	Host family
Asco-Basi	0.05	0.06	0.11
Asco-Oomy	0.09	0.07	0.10
Basi-Oomy	0.03	0.00	0.07

Asco = Ascomycota, Basi = Basidiomycota, Oomy = Oomycota.

The results of the Cramer's V test indicate a significant relationship ($p < 0.05$) between the fungal phylum, order, family, genus, and species, and the host family (Table 3). The results further indicate that the fungal order, family and species ($p = 0.01$) exhibit a significant relationship with the host genus, but the association between fungal taxa at all levels and host species was not significant. However, as the level of taxonomic resolution decreases from phylum to species level, the specificity of fungal taxa towards host species decreases due to the species and generic diversity within individual plant families.

The host dependence pattern among various fungal phyla was studied using the Jaccard Index of Similarity (JIS) among various fungal phyla pairs. The results revealed that JIS values ranged between 0.05–0.11 for the Ascomycota-Basidiomycota pair and between 0.07–0.10 for the Ascomycota-Oomycota pair (Table 4), while the range of values was lower (0.00–0.07) for the Basidiomycota-Oomycota pair. This may be related to the findings in Table 2, where the similarity of host species, genus, and family was compared in terms of their distribution across different phyla. It was observed that only *Amomum subulatum* Roxb. (Zingiberaceae) was a common host to Ascomycota, Basidiomycota, and Oomycota.

Conclusions

A checklist of phytopathogenic fungi is an important reference for understanding the distribution of plant pathogenic fungi and their associated plant hosts in a given region. The current study provides a comprehensive overview of the diversity of phytopathogenic fungi and their hosts in Sikkim, India which is a region of prime biodiversity importance. The study also highlights some intriguing findings, including phytopathogens that are specific to plant reproductive organs, such as *Microbotryum emodense* (specific to anthers) and *Sporisorium setaricolum* (specific to ovaries). Additionally, the study identifies phytopathogens that are linked to human health, such as allergenic contaminants commonly found in indoor environments, such as *Cephalosporium* spp., *Cladosporium* spp., *Curvularia* spp., and *Torula herbarum*. The study also notes phytopathogens that play a significant role in the production of antibiotics, mycotoxins, and enzymes, including Cephalosporin C from *Cephalosporium acremonium*, mycotoxins from *Phyllosticta sorghina* and *Stenocarpella maydis*, and polyurethane degrading Serine Hydrolase from *Pestalotiopsis microspora*.

It was observed that the diversity of phytopathogenic fungi is closely linked to the diversity of plant hosts they infect. The study found that the fungi's affinity for their host plants was significant at the family level, but became less specific at the infra-familial level. Thus, it is important to carefully document the infra-familial host affinities. Some examples of these affinities from the study include *Seifertia*'s specificity towards *Rhododendron*, *Monilinia* spp. for Ericaceae, *Puccinia ustalis* for Ranunculaceae, and *Erysiphe sikkimensis* for *Castanopsis* and *Quercus*.

Accurate identification of the causal agents of plant diseases is imperative for effective disease management. In some cases, initially assumed causes of the disease may not be the actual pathogen. For instance, *Pestalotiopsis royenae*, an endophyte, has previously been implicated in causing leaf streak in *Amomum subulatum*, however, recent evidence suggests that the tea mosquito bug (*Helopeltis theivora*) may be the more prevalent agent of the symptoms. Therefore, in this case the management efforts should prioritize control of *H. theivora* over *P. royenae*. Furthermore, endophytes and saprophytes (facultative parasites) may serve as a significant pool of biotrophs for immunocompromised hosts. In light of this, a re-evaluation of the endophytic biology of fungi such as *Cryptospora caryae*, *Curvularia eragrostidis*, *Dichotomopilus funicola*, and *Leptosphaerulina trifolii* is necessary.

In the management of plant diseases, knowledge about alternative hosts can also be useful. For example, it is not advisable to cultivate *Luffa aegyptiaca* near *Solanum betaceum* plants that have leaf spots, as both are hosts of *Alternaria alternata*. Similarly, planting *Brassica* spp. near *Vigna* spp. should be avoided, as *Rhizoctonia solani* has been identified as a common factor causing root and collar rot in *Brassica juncea* and *B. rapa*, as well as aerial blight in *Vigna mungo*, *V. radiata*, and *V. umbellata*. An integrated and synergistic approach to disease management is essential, particularly for heteroecious rust fungi such as *Melampsoropsis elaeocarpi* and *Stilbechrysomyxa himalensis*, which have pycnidial stages on *Picea* and *uredial* and *telial* stages on members of Ericaceae and Elaeocarpaceae.

Furthermore, strains within fungal species are often classified into different pathotypes or formae speciales based on their host range, such as those found within *Alternaria* spp. In order to effectively manage plant diseases, it is important to identify phytopathogens at these levels and to study their specificity to host species and cultivars. Additionally, documenting the locations of disease incidence is crucial for spatial monitoring and prompt disease management to prevent its spread.

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Conflict of interest

The authors declare that they have no conflict of interest.

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