Arch Lebensmittelhyg 68,
39–47 (2017)
DOI 10.2376/0003-925X-68-39

ISSN 0003-925X

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Review:

Fungi in raw insect and arachnid taxa containing species used in human entomophagy: a review

Übersichtsarbeit:

Pilze in rohen Insekten- und Spinnentiertaxa, die für den menschlichen Konsum genutzte Arten beinhalten: eine Übersicht

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Summary

Little is known of the microbiological hazards associated with consumption of edible insects and spiders. The present review summarizes the potential of fungi to impair food hygiene and food safety for the human consumer. Fungi interact with insects and spiders very diversely, ranging from physiologically necessary to entomopathogen. Raw arthropods, usually collected from their original environment, may carry a variety of fungi of which some have the potential to cause disease also in humans (e. g. *Aspergillus* spp., *Fusarium* spp., *Mucor* spp. and *Aureobasidium pullulans*) and may act as food spoilers. Regarding mycosis, most of these pathogens have been reported only as sporadic opportunists affecting immunocompromised patients. This however is also true for other foodstuffs. A more intensive usage of edible arthropods (especially of insects) is intended for the future, and so, proper hygienic means must be undertaken to ensure consumers' safety. These means may comprise those already implemented for common foodstuffs and those practised traditionally by most entomophagous communities.

Keywords: food-borne disease, allergy, mycosis, zoonosis, human

Zusammenfassung

Wenig ist über die mikrobiologischen Gefahren beim Konsum von Speiseinsekten und -spinnentieren bekannt. Die vorliegende Übersichtsarbeit fasst das Potential der Pilze zusammen, die Lebensmittelhygiene und -qualität für den Verbraucher zu beeinträchtigen. Pilze interagieren auf sehr unterschiedliche Weise mit Insekten und Spinnentieren, angefangen als physiologische Notwendigkeit bis hin zum entomopathogenen Keim. Rohe Gliederfüßer, typischerweise in ihrer eigenen Umwelt gesammelt, können eine Reihe von Pilzen enthalten, von denen einige als potentielle Krankheitserreger für den Menschen agieren (z. B. *Aspergillus* spp., *Fusarium* spp., *Mucor* spp. und *Aureobasidium pullulans*) oder als Verderbniskeime auftreten können. Hinsichtlich der Mykosen wurden die meisten dieser Erreger lediglich als sporadisch auftretende Opportunisten bei immunsupprimierten Patienten gefunden. Allerdings wurden sie auch von anderen Lebensmitteln isoliert. Eine zukünftige, intensivere Nutzung essbarer Gliederfüßer (insbesondere Insekten) bedingt die Einführung angemessener Hygienemaßnahmen zum Schutze des Verbrauchers. Diese Maßnahmen können die ohnehin für bekanntere Lebensmittel und die traditionell von den meisten entomophagen Völkern getroffenen Vorkehrungen umfassen.

Schlüsselwörter: von Lebensmitteln übertragene Erkrankungen, Allergie, Mykose, Zoonose, Mensch

Introduction

FAO recognized entomophagy (including, for this paper, arachnophagy, the consumption of arachnids) as one possibility to improve nutrient supply, considering commercial insect production a sustainable method to ensure this supply. Thus, entomophagy passes from traditional consumption to commercial farming of species with a promising future as ordinary lifestock, e. g. some orthopterans (grasshoppers and crickets), coleopterans (beetle grubs), lepidopterans (moth caterpillars and pupae), dipterans (fly larvae and pupae), and hymenopterans (bee, ant, and wasp larvae and pupae). Notable efforts in this direction have been made in Southeast Asia and South Africa, but European companies in e.g. the Netherlands, Belgium, and Germany have also started producing crickets, mealworms and black soldier flies (van Huis et al., 2013).

The current situation in the European Community (EU), a traditionally non-entomophagous region, regarding entomophagy is characterised by transition. In 2014, Belgium and the Netherlands presented interim solutions to approach sanitary control of edible insects (FASFC, 2014a; FASFC, 2014b; NVWA, 2014). Only the Belgian regulation considers fungi and yeasts. In 2015, a scientific opinion by the EFSA was published (EFSA, 2015), and an intended amendment of the novel food regulation 258/97 includes insect and insect products. The EFSA statement also only refers to 'fungi and yeasts'. Both papers regard fungi as relevant risk factors for the consumer, moreover as the genera mentioned there (*Aspergillus, Penicillium,* and *Fusarium*) are mycotoxin producers.

However, the mycobiome of arthropods is characterised by a complex net of interactions between fungus and host, ranging between physiological and pathological. Some fungi are vital symbionts for the insect, while others are powerful entomopathogens used e. g. in the biological control of pest insects. Under certain circumstances, physiologically-acting fungi may become opportunistic pathogens. The array of fungi varies also according to the habitat and the stage of development (Tanada and Kaya, 1993). For the honeybee *(Apis mellifera),* these interactions were reviewed recently (Grabowski and Klein, 2015), and the basic pattern may be extrapolated to other arthropods: the microbiome of these animals changes because of a constant uptake and release of microorganisms. A similar condition (with due changes in quality and quantity of the fungal populations) is expected when insects are farmed.

Starting from the EFSA statement, the present review focuses on the fungal findings of raw insects and arachnids, evaluating their potential risk for the human consumer.

Methods

NCBI and Google Scholar were the search engines used. Considering the recent major revision of the regnum of fungi (s. below), all scientific names were cross-checked using the 'Index Fungorum' (Index).

The list by de Jongema (2015) served as a reference for the edible insects. Arthropod species were merged according to two principles: on one hand, when the literature only cited generically ('beetles', 'bugs', 'insects'), this generic term was kept. When, on the other hand, arthropod species were well-identified, the next higher taxon (family, order, etc.) was recorded as it is possible that other members of the same taxon may also become infected with the same fungus. A record was used in this review if either the species or the next higher taxon was also included in the list of de Jongema (2015).

According to the type of interaction, several risk classes were defined:

- Pathogens affecting both arthropods and humans (class I)
- Pathogens affecting only arthropods (class II)
- Pathogens affecting only humans (class III)
- spoilage microorganisms transmitted via passive transport (class IV)

Active pathogen vectors (e. g. haematophageous flies or bugs) are not consumed traditionally and were excluded from the review. Types I and III were not termed 'zoonosis' because a direct transmission was almost never recorded. Instead, the data of this review pinpoints those cases in which one and the same fungus was encountered in arthropod and human hosts.

Results

Taxonomical problems

Fungi taxonomy has been subjected to a series of changes from 2013 on, when holomorph taxa were introduced. As an example, *Cephalosporidium* was a very extensive entomopathogenic genus which was split into many new genera, among them the human-pathogenic genus *Acremonium.* When a publication cites '*Cephalosporidium* spp.' to be entomopathogenic, this may or may not also refer to *Acremonium* spp. Many *Filobasidiella* spp. were re-located to be part of *Cryptococcus neoformans* and entomopathogenic *Vericillium* spp. were organised as *Lecanicillium* spp., to cite only some examples. This implies a thorough tracing and cross-checking of all the literature in order to assess the currently valid, scientific name. In fact, much information regarding rather uncommon taxa should be interpreted with caution

Entomopathogenic fungi

Fungi (incl. yeasts and microsporidia) occur in many arthropod species (Amadi et al., 2005; Gorham, 1979; Šřamová et al., 1992). They are very frequent pathogens, affecting and interacting with their hosts in many different ways. The total number of entomopathogenic fungi is estimated to be approx. 50,000. In contrast, fungal pathogens for mammal amount to a few hundred only, probably due to vertebrate endothermy (Robert and Casadevall, 2009).

Most data originated from raw arthropod specimens caught from the wild. This is important to notice from the food hygiene point of view, since this mycobiome not necessarily reflects the situation while farming insects commercially.

Table 1 summarizes fungi encountered in insects generically. Subsequently, data regarding specific insect (Tab. 2 to 7) and spider (Tab. 8) taxa are contemplated.

The tables show a great variety of fungi affecting arthtropods in 411 genera and species, grouped in 45 families (plus some species currently *incertae sedis*) across all major taxa. *Cordycipitaceae, Ophiocordycipitaceae* and *Entomophthoraceae* were the most numerous families. For the tables 1 to 8, a more specific taxonomic layout was not chosen because of space.

TABLE 1: *Fungi affecting insects in general (Didier, 2005; Fotedar et al., 1991; Harwood and James, 1987; Henke et al., 2002; Ignoffo, 1973; Leatherdale, 1970; Mathis et al., 2005; Mpuchane et al., 2000; Samson, 1974; Srivastava et al., 2009; Tanada and Kaya, 1993; Wang et al., 2011; Weiss, 2001); see text for class definitions.*

Familia	Genus/species	class
Amoebidiaceae	*Amoebidium parasiticum*	II
Ancylistaceae	*Conidiobolus coronatus*	I
Asellariaceae	*Asellaria aselli*	II
Basidiobolaceae	*Basidiobolus ranarum*	I
Clavicipitaceae	*Lecanicillium* spp., *Metarhizium anisopliae* *Metarhizium flavoviride, M. robertsii, Moelleriella amomi*	I II
Cordycipitaceae	*Akanthomyces* spp., *Aschersonia aleyrodis, Cordyceps carnata, Gibellula aranearum, Isaria farinosa, I. fumosorosea, Torrubiella albotomentosa, T. aranicida, T. columbiana* *Beauveria bassiana, B. brongniartii*	II I
Culicosporellidae	*Culicosporella lunata*	II
Eccrinaceae	*Taeniella carcini*	II
Entomopthoraceae	*Entomophaga grylli*	II
Laboulbeniaceae	*Fanniomyces ceratophorus, Filariomyces forficulae, Hesperomyces virescens, Trenomyces histophtorus*	II
Leptolegniaceae	*Aphanomycopsis sexualis*	II
Meristacraceae	*Meristacrum* spp.	II
Metschnikowiaceae	*Metschnikowia biscubidata var. biscupidata*	II
Nectriaceae	*Calonectria* spp. *Cosmospora flammea* *Fusarium entomophilum*	I II I
Nosematidae	*Brachiola algerae* *Nosema pyraustra*	I II
Ophiocordycipitaceae	*Hirsutella entomophila, H. illustris, H. thompsonii, Hymenostilbe* spp., *Ophiocordyceps aphodii, O. bispora O. sinensis, Tolypocladium cylindrosporum*	II
Pleistophoridae	*Pleistophora* spp.	I
Pythiaceae	*Lagenidium giganteum*	II
Saccharomycetaceae	*Saccharomyces cerevisiae* *Blastodendrion pseudococci*	I II
Septobasidiaceae	*Septobasidium clelandii, Uredinella* spp.	II
Tremellaceae	*Filobasidiella* spp. (≈ *Cryptococcus neoformans*)	I, IV
Trichocomaceae	*Aspergillus* spp., *A. flavus, A. fumigatus, A. ochraceus, A. parasiticus, A. repens, A. tamarii, A. versicolor* *Penicillium* spp.	I, IV III
Trichodomataceae	*Tilachlidiopsis nigra*	II
Tubeufiaceae (incertae sedis)	*Podonectria coccicola* *Candida* spp., *C. albicans* *Candida apicola, C. apis, Mycoderma* spp., *Myiophagus ucrainicus, Pleurodesmospora* spp., *Spicaria* spp., *Sporodiniella umbellate, Stempellia* spp., *Tetranacrium* spp., *Tilachlidium* spp.	II I II

Cordycipitaceae was the most frequent family in most arthropod orders, with 17 % prevalence in insects and 26 % in spiders. Whithin insects, they usually ranged on first place, with the exception of hemipterans and dipterans (second place each and *Entomophthoraceae* being more frequent), and lepidopterans in which *incertae sedis* taxa prevailed, followed by *Ophiocordycipitaceae.* Beyond that, each order presented a specific spectrum of fungi. (Wang et al., 2011) also observed some fungi that attack a great variety of insects, while some only affect a few or only one species. However, these data must be seen in relation to the taxonomic changes that took place within the fungi. The *Metarhizum* species affecting grasshoppers was listed as 'M. acridium', being the only species of the genus affecting these orthopterans. Nowadays, it is synonymized with *M. anisopliae* (found on many different insect species).

Fungi colonize arthropods according to their habitat; *Metchnikowia* spp. is associated with flowers and is therefore found on many insects that frequent flowers.

From the food safety point of view, a few key facts deserve attention:

TABLE 2: *Fungi affecting bugs, cicadas, hoppers, scale insects (Hemiptera) (Jay et al., 2005; Leatherdale, 1970; Samson, 1974; Srivastava, et al., 2009; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
hemipterans		
Ancylistaceae	*Conidiobolus obscurus*	II
Clavicipitaceae	*Conoideocrella tenuis, Hypocrella calendulina, H. disciformis, H. hirsuta, H. luteola, H. macrostoma, H. panamensis, H. siamensis, Moelleriella africana*	II
Cordycipitaceae	*Aschersonia minutispora, A. suzukii, Torrubiella barda, T. brunnea, T. fusiformis, T. hemipterigena, T. iriomoteana, T. lecanii, T. petchii, T. piperis, T. psyllae, T. sphaerospora, T. sublintea, T. superficialis*	II
Entomopthoraceae	*Entomophthora muscae, E. planchoniana*	II
Ophiocordycipitaceae	*Hymenostilbe furcata*	II
lygaeid bugs		
Entomopthoraceae	*Entomophthora* spp.	II
Trichocomaceae	*Paecilomyces* spp.	I
pentatomid bugs		
Entomopthoraceae	*Zoophthora pentatomis*	II
homopterans		
Clavicipitaceae	*Hypocrella zhongdongii, Lecanicillium aphanocladii, L. muscarium* *Lecanicillium lecanii*	II I
Cordycipitaceae	*Aschersonia insperata, Engyodontium geniculatum, Torrubiella siamensis*	II
Entomopthoraceae	*Entomophthora aphrophorae*	II
Ophiocordycipitaceae	*Hirsutella acridiorum*	II
cercopid froghoppers		
Entomopthoraceae	*Batkoa apiculata, Entomophthora sphaerosperma*	II
Ophiocordycipitaceae	*Hirsutella atewensis*	II
cicadas		
Clavicipitaceae	*Metarhizum viridulum, Nomuraea owariensis*	II
Cordycipitaceae	*Isaria cicadae*	II
Entomopthoraceae	*Massospora cicadettae, M. pahariae*	II
Ophiocordycipitaceae	*Purpureocillium lilacinum*	I
cicadellid leafhoppers		
Entomopthoraceae	*Pandora cicadellis*	II
Ophiocordycipitaceae	*Hirsutella guyana, H. nivea*	II
aphids		
Entomopthoraceae	*Entomophaga bukidnonensis, Furia triangularis, Zoophthora aphidis*	II
Ophiocordycipitaceae	*Hirsutella aphidis*	II
scale insects		
Clavicipitaceae	*Lecanicillium evansii*	II
Dothioraceae	*Aureobasidium pullulans*	I, IV
Myriangaceae	*Myriangium duriaei*	II
Nectriaceae	*Microcera coccophila, M. diploa, M. larvarum, M. rubra*	II
Saccardiaceae	*Angatia* spp.	II
Ophiocordycipitaceae	*Hymenostilbe lecaniicola, Hirsutella cryptosclerotium, H. sphaerospora, Ophiocordyceps clavulata*	II

Journal of Food Safety and Food Quality 68, Heft 2 (2017), Seiten 23–52

TABLE 3: *Fungi affecting dragonflies, cockroaches, orthopterans, and termites (Odonata, Blattodea, Orthoptera, Isoptera) (Casique Valdes et al., 2012; Fotedar, et al., 1991; Jay et al., 2005; Johny et al., 2009; Leatherdale, 1970; Samson, 1974; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
libellulid skimmers		
Clavicipitaceae	*Metarhizium libelullae* (sic)	II
cockroaches		
Cordycipitaceae	*Torrubiella blattae*	II
Mucoraceae	*Mucor* spp.	III, IV
	Mucor hiemalis	I
Ophiocordycipitaceae	*Hymenostilbe ventricosa*	II
Pleosporaceae	*Alternaria* spp.	III, IV
Rhizopodaceae	*Rhizopus* spp.	III, IV
Trichocomaceae	*Aspergillus niger*	I, IV
orthopterans		
Ophiocordycipitaceae	*Hirsutella acridiorum*	II
grasshoppers		
Entomopthoraceae	*Entomophaga calopteni, E. grylli*	II
Nosematidae	*Nosema acridophagus, N. locustae*	II
romaleid grasshoppers		
Encephalitozoonidae	*Encephalitozoon romalae*	II
tettigoniid grasshoppers		
Trichocomaceae	*Paecilomyces reniformis*	II
termites		
Ophiocordycipitaceae	*Ophiocordyceps octospora*	II

- Scientific investigation has been centered on pathogens for pests. Only some pest species are actually consumed, but fungal pathogens may also be expected in those insects which are regularly eaten. Corresponding data is lacking.
- Arthropod mycosis may be external or internal; if the latter is the case, mycosis may pass undetected, moreover if the animals are already dead.
- Literature must be reviewed carefully regarding taxonomic information in order to use the currently accepted term (see above).
- During regular foodstuff analysis, fungi are frequently reported generically. If a closer look took place, then only 'typical' fungal genera as *Aspergillus* spp. or *Mucor* spp. are monitored.

There is few data on fungi in processed insects. Mpuchane et al. (2000) studied the fungal population inside dried saturniid caterpillars of *Imbrasia bellina* ('mopane'). With 47 % of positive findings, *Aspergillus* spp. was the most common fungus present in this product. Contents of aflatoxin ranged between 0 and 50 µg/kg. *Penicillium, Chaetomium* and *Fusarium* were isolated (each 5 % or below) from mopane. However, other fungi were only reported generically, e. g. as *Phycomyctes* (currently *Zygomycota*; 15 %), dimatiaceous moulds (including *Alternaria* spp.; 3 %) and 'other fungi' (26 %). Thus, approx. one third of the fungi present in phane were not identified further, possibly because they did not belong to the 'common' genera. The risks associated with these unidentified fungi remain unknown. The amounts of aflatoxins may pose a threat on the long run. Although not entirely cleared, poor manufacture hygiene could be responsible for this fungal population. Fungal growth is currently held responsible for the relatively short storage time; phane will eventually display mycelial growth and powdery discoloration.

Amadi et al. (2005) analysed fresh emperor moth *(Saturniidae: Bunaea alcinoe)* caterpillars, and obtained fungal counts 2.1 x 10^6 and 1.3 x 10^6 cfu/g on the skin and in the intestines, resp.

Human pathogens

Table 9 to 13 contain human-pathogenic groups (in classes) according to their taxonomy. The interaction between man and fungi are likewise complex. Most fungi associated with arthropods cannot survive in a human host because of the body temperature (Ignoffo, 1973). This may vary from among species. Human-pathogenic *Paecilomyces* spp. do not affect insects and vice versa (Samson, 1974). Again, the taxon may be decisive in the kind of relation between fungus and host. *Entomophthorales* may affect healthy individuals while *Mucorales* usually act as opportunists that can disseminate in YOPI (young, old, pregnant, immunocompromised) (Ribes et al., 2000). Of the approx. 400 human-pathogenic fungus species, most can establish a

TABLE 4: *Fungi affecting wasps, sawflies, ants, and bees, (Hymenoptera) (Bischoff, 2005; Hughes et al., 2011; Jay et al., 2005; Leatherdale, 1970; Samson, 1974; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
wasps		
Clavicipitaceae	*Metarhizium polistis*	II
Ophiocordycipitaceae	*Ophiocordyceps sphecocephala, Polycephalomyces ditmarii*	II
Cordycipitaceae	*Torrubiella formicarum, T. pseudogibellulae*	II
diprionid sawflies		
Entomopthoraceae	*Entomophaga diprionis*	II
tenthredinid sawflies		
Entomopthoraceae	*Entomophthora tenthredinis, Erynia athaliae*	II
ants		
Burenellidae	*Burenella dimorpha*	II
Cordycipitaceae	*Isaria amoenerosea*	II
Entomopthoraceae	*Pandora formicae, P. myrmecophaga*	II
Hypocreomycetidae	*Stilbella dolichoderinarum, S. buquettii var. formicarum*	II
Ophiocordycipitaceae	*Hirsutella acerosa, H. ovalispora, H.o. var. dolichoderi, H. sporodochialis, H. stillbelliformis, H.s. var. dolidocheri, H.s. var. gnamptogenyos, H.s. var. monacidis, H.s. var. myrmicarum, H.s. var. ponerinarum, Hymenostilbe aurantiaca, Ophiocordyceps sphecocephala, O. unilateralis, Paraisaria myrmicarum*	II
Pleosporaceae	*Alternaria alternariae*	II
(incertae sedis)	*Aegeritella lenkoi, A. roussillonenis, A. superficialis, A. tuberculata*	II
apoid bees		
Ascosphaeraceae	*Ascosphaera acerosa, A. aggregata, A. apis, A. asterophora, A. celerrima, A. cinnamomea, A. duoformis, A. fusiformis, A. larvis, A. naganensis, A. osmophila, A. parasitica, A. pollenicola, A. proliperda, A. scaccaria, A. solina, A. subcuticularis, A. tenax, A. torchioi, A. variegata, A. verrucosa, A. xerofila, Bettsia alvei*	II
Davidiellaceae	*Cladosporum cladosporioides*	I, IV
Dothioraceae	*Aureobasidium pullulans*	I, IV
Hypocreaceae	*Acrostalagmus* spp.	I
Metschnikowiaceae	*Metschnikowia kunwiensis*	II
	Metschnikowia pulcherrima	I
Nosematidae	*Nosema apis, N. bombycis*	II
Trichocomaceae	*Penicillium aurantiogriseum*	I
	Talaromyces funiculosus	II
(incertae sedis)	*Cephalosporium* spp., *Chaetophoma quercifolia*	II

TABLE 5: *Fungi affecting beetles (Coleoptera) (Leatherdale, 1970; Samson, 1974; Tanada and Kaya, 1993; Vega et al., 2008); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
beetles		
Clavicipitaceae	Lecanicillium kalimantanense, L. muscarium, L. pissodis	II
Cordycipitaceae	Isaria amoene-rosea, I. coleopterorum	I
Ophiocordycipitaceae	Hirsutella dendritica, Ophiocordyceps entomorrhiza	II
(incertae sedis)	Sorosporella uvella	II
carabid beetles		
Cordycipitaceae	Cordyceps memorabilis	II
Entomopthoraceae	Furia zabri	II
cerambycid beetles		
Cordycipitaceae	Beauveria malawiensis	II
chrysomelid beetles		
Entomopthoraceae	Pandora suturalis	II
curculionid beetles		
Ancylistaceae	Conidiobolus osmodes	II
Bionectriaceae	Clonostachys rosea	II
Cordycipitaceae	Isaria javanica	II
Entomopthoraceae	Entomophthora coleopterum	II
Metschnikowiaceae	Metschnikowia typographi	II
elaterid beetles		
Ophiocordycipitaceae	Hirsutella rubripunctata, Syngliocladium cleoni	II
nitidulid beetles		
Metschnikowiaceae	Metschnikowia cerradonensis, M. colocasiae, M. continentalis, M. c. var. borealis, M. hamakuensis, M. hibisci, M. kamakouana, M. lochheadi, M. mauinuiana, M. orientalis, M. santaceciliae, M. similis	II
scarabeid beetles		
Clavicipitaceae	Metarhizium frigidum, M. pinghaense	II
tenebrionid beetles		
Entomopthoraceae	Entomophaga lagriae	II

commensal status in which they are able to survive in the host, but flaws in the immune system may trigger systemic, increasingly-documented mycoses (Henke et al., 2002). Many fungi are facultative pathogens, and uncommon and/or newly described species may produce numerous diseases. A proper diagnosis via culture is difficult due to unstable morphology, atypical appearances in clinical cases and a slow rate of sporulation. Thus, molecular biology methods are preferred (Pagiotti et al. 2011).

Fungi may enter the host via the oral, respiratory or skin contact route. Some fungi, including *Zygomycetes,* have reportedly been transmitted via insect and spider bite (Ribes et al., 2000).

Regarding the fungi found in insects in general (Tab. 1), human-pathogenic ones account for 31 % of all listed genera and species, in spiders (Tab. 8) only for 3 %. However, insects have been studied more intensively than spiders, and concrete data regarding the edible theraphosid spiders are missing, a condition expected to continue. Thus, spiders will not be considered further in this paper.

Some fungi contain mycotoxins, e. g. *Alternaria* spp. (alternariol, alternariol monomethyl ether, altenuene, tenuazonic acid, altertoxin-I), *Aspergillus* spp. (aflatoxins B1, B2, G1, G2, ochratoxin A, ochratoxin B, sterigmatocystin), and *Penicillium* spp. (patulin, penicillic acid) (Jay et al., 2005).

Apart from general pathogens (Tab. 1), the prevalence of human-pathogenic fungi (Tab. 2 to 7), varied from 0 (dragonflies, orthopterans, termites, hemipterans, beetles, mayflies, and flies) over 4 (hemipterans) and 7 (hymenopterans) to 17 (moths) and 71 % (cockroaches).

Tables 9 to 13 focus on those fungi that are reportedly human-pathogenic. Most of them were ascomycetes (Tab. 8 to 12). Regarding other *Ascomycota* orders as summarized in those tables, *Cephalosporium* spp. was reported to cause mycetoma (Fincher et al., 1991), *Chaetophoma* spp. onychomycosis (Singh and Barde, 1986), and *Verticillium menisporioides keratitis* (Karsten et al., 2012). *Zygomycetes* are referred to in Tab. 13. *Filobasidiella* spp. corresponds largely to *Cryptococcus neoformans,* producing cryptococcosis, meningitis, encephalitis, and pneumonia (Velagapudi et al., 2009).

The taxonomic status of microsporidia is still debated. *Pleistophora* spp. has been associated with human microsporidiosis, *Brachiola algerae* with keratitis, cerebrovascular infarction, myositis, skin infections and *Nosema* spp. with keratitis (Cali et al., 2005;

TABLE 6: *Fungi affecting mayflies and butterflies (Neuroptera and Lepidoptera) (Ignoffo, 1973; Jay et al., 2005; Leatherdale, 1970; Mpuchane, et al., 2000; Samson, 1974; Srivastava et al., 2009; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
mayflies		
Legeriomycetaceae	Legeriomyces aenigmaticus, L. algonquinensis, L. dolabrae, L. leptocerci, L. rarus, L. whitneyi	II
nemourid stoneflies		
Entomopthoraceae	Erynia plecopteri	II
butterflies		
Clavicipitaceae	Lecanicillium lecanii	I
	Nomuraea rileyi	II
Cordycipitaceae	Cordyceps tenuipes, C. tuberculata, Isaria. amoene-rosea, I. ghanensis, I. javanica, I. leprosa, Torrubiella minutissa, T. ochracea, T. sericicola, T. wallacei	II
Entomopthoraceae	Entomophaga aulicae, E. maimaiga, Furia virescens	II
Nosematidae	Nosema bombycis	II
Ophiocordycipitaceae	Hirsutella exoleta, H. leizhouensis, H. longicolla, H. l. var. cornuta, H. sinensis, H. subulata, H. yunnanensis var. tennui-synnemata	II
Trichocomaceae	Paecilomyces ramosus	II
(incertae sedis)	Sorosporella uvella	II
arctiid butterflies		
Cordycipitaceae	Beauveria velata	II
Entomopthoraceae	Furia creatonoti	II
Nectriaceae	Fusarium spp.	I
crambid butterflies		
Clavicipitaceae	Metarhizium globosum	II
Metschnikowiaceae	Metschnikowia andauensis	II
hepialid butterflies		
Clavicipitaceae	Metarhizium guizhouense	II
Cordycipitaceae	Akanthomyces aculeatus	II
Ophiocordycipitaceae	Hymenostilbe sphingum, Ophiocordyceps gracilis	II
noctuid butterflies		
Burenellidae	Vairimorpha necatrix	II
Entomopthoraceae	Tarichium megaspermum	II
Nosematidae	Nosema heliothidis	II
pierid butterflies		
Entomopthoraceae	Furia pieris	II
saturniid butterflies		
Chaetomiaceae	Chaetomium spp.	III
sphingid butterflies		
Cordycipitaceae	Cordyceps militarys, Isaria ochracea	II
tortricid butterflies		
Clavicipitaceae	Lecanicillium attenuatum	I
Nosematidae	Nosema fumiferanae	II

TABLE 7: *Fungi affecting flies (Diptera) (Leatherdale, 1970; Samson, 1974; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
flies		
Clavicipitaceae	*Metarhizium gigas*	II
Davidiellaceae	*Cladosporum aphidis*	II
Entomopthoraceae	*Batkoa limoniae, Entomophthora conglomerata, E. culicis, E. domestica, E. muscae, E. planchoniana, E. richteri, E. tipulae, Furia americana, F. ithacensis, Pandora dipterigena, P. echinospora, P. muscivora, Strongwellsea castrans, S. magna*	II
Ophiocordycipitaceae	*Hymenostilbe muscaria*	II
Trichocomaceae	*Paecilomyces suffultus*	II
calliphorid flies		
Entomopthoraceae	*Pandora borea*	II
chironomid flies		
Saprolegniaceae	*Couchia amphora, C. circumplexa, C. limnophila*	II
drosophilid flies		
Metschnikowiaceae	*Metschnikowia hibisci*	II
Clavicipitaceae	*Harposporium scyodes*	II
Nosematidae	*Nosema kingi*	II
muscid flies		
Metschnikowiaceae	*Metschnikowia vanudenii*	II
Ophiocordycipitaceae	*Ophiocordyceps forquingnoni*	II
sarcophagid flies		
Entomopthoraceae	*Pandora bullata*	II
tephritid fruit flies		
Clavicipitaceae	*Lecanicillium muscarium*	II
tipulid flies		
Cordycipitaceae	*Cordyceps tenuipes*	II
tipulid flies		
Entomopthoraceae	*Zoophthora humberi*	II

Curry et al., 2007; Field et al., 2012; Mathis et al., 2005; Weiss, 2001).

Evaluation

As with other foodstuffs, the risks by arthropod-associated fungi will depend on the production level and the task of the individual along the food-generating chain. Food producers face different risks with regard to the foodstuff than a consumer would. There are several levels of automation in arthropod usage for food (based on Menzel and D' Alusio (1998):

- During direct obtention and consumption of fresh insects and spiders (hunter-gatherers or people producing arthropods for private consumption), handlers are confronted with fungi of classes I to III. They are likely to exclude animals affected by class I and II fungi as well as dead animals (class IV), so their risks are mainly class III fungi.
- In a next level, animals are gathered/reared and sold on local markets, either raw or processed. Additional risks may appear for the consumer by class III (if undetected before) and class IV fungi, if storage was inadequate. When amounts of animals surpass the level of own consumption, control decreases and the risk by class I and II fungi increases, particularly when the disease is subclinical.
- Several steps between producers and the end-consumer may be occurring. The longer this chain becomes, the more the risk of human pathogens/spoilage increases, in addition to risks formulated previously.

Completely entomopathogenic fungi (class II) are not expected to pose a risk for anyone handling edible arthropods. They become increasingly important for farmers because many insect farms are operated using and all-in-all-out system (Hanboonsong et al., 2013). Entomopathogenic fungi will affect the stock health, its quality and production yield, and are likely to extend to an entire batch (Tanada and Kaya, 1993).

Fungi associated with human disease pose a risk for farm and processing personnel (making dust masks mandatory, as in porcine and poultry production), as well as for the consumer (particularly when being YOPI) if processing failed to eliminate these risks (e.g. mycotoxin control). Fungi may affect yield and quality if storage was inefficient.

All this suggests a relatively large risk. However it should be considered that most of these fungi are dispersed ubiquitously in the environment, and arthropods and humans can acquire them from many sources. More common foodstuffs also yield many of these fungi (Jay et al., 2005). Most of the pathogens mentioned here are opportunistic,

TABLE 8: *Fungi affecting spiders (Arachnida) (Ignoffo, 1973; Leatherdale, 1970; Samson, 1974; Srivastava et al., 2009; Tanada and Kaya, 1993); see text for class definitions.*

Insect group/ Familia	Genus/ species	class
arachnida		
Clavicipitaceae	*Lecanicillium araneicola, L. muscarium, L. tenuipes, Nomuraea atypicola, N. rileyi*	II
	Lecanicillium lecanii	I
Cordycipitaceae	*Akanthomyces aranearum, A. cinereus, A. koratensis, A. longisporus, A. ovolongatus, A. websteri, Engyodontium aranearum, Gibellula aranearum, G. brunea, G. clavulifera, G. dabieshanensis, G. dimorpha, G. globosa, G. globosostipitata, G. mainsii, G. mirabilis, G. unica, Torrubiella alba, T. alboglobosa, T. albolanata, T. arachnophila, T. aranicida, T. aurantia, T. clavata, T. dabieshanensis, T. dimorpha, T. ellipsoidea, T. farinacea, T. flava, T. formosana, T. globosa, T. globosoides, T. globostipitata, T. inegoensis, T. longissima, T. mamillata, T. minuta, T. minutissima, T. miyagiana, T. neofusiformis, T. oblonga, T. ooaniensis, T. pallida, T. ratticaudata, T. rokkiana, T. rosea, T. ryogamimontana, T. ryokyuensis*	II
Ophiocordycipitaceae	*Hirsutella darwinii, Hymenostilbe spiculata, H. verrucosa, Synggliocladium aranearum*	II
Plectosphaerellaceae	*Verticillium menisporioides*	I
(incertae sedis)	*Spicaria spp., S. stricta*	II

TABLE 9: *Human-pathogenic Ascomycota: Dothideomycetes (Chan et al., 2011; Chowdhary et al., 2012; Horner et al., 1995; Karsten et al., 2012; Kim et al., 2012; Kurup et al., 2000; Morais et al., 2011; Revankar and Sutton, 2010; Sorenson, 1999; van de Sande, 2013).*

Ordo/ Familia	Genus/ species	Disease
Capnodiales		
Davidiellaceae	*Cladosporum spp.*	asthma, keratitis, mycetoma
	Cladosporum cladosporioides	allergy, (sub)cutaneous and deep mycoses
Dothideales		
Dothioraceae	*Aureobasidium pullulans*	septicaemia, chromoblastomycosis, disseminated mycoses, pneumonitis, peritonitis, phaeohyphomycosis
Pleosporales		
Pleosporaceae	*Alternaria spp.*	asthma, bronchopulmonary mycosis, deep cutaneous mycosis, (sub)cutaneous phaeohyphomycosis, keratitis, mycotoxins

TABLE 10: *Human-pathogenic Ascomycota: Eurotiomycetes, order Eurotiales, family Trichocomaceae (Babamahmoodi, 2015; Burgner et al., 1998; Corry and Kheradmand, 2009; D'Antonio et al., 1997; Fazakas, 1938; Horner et al., 1995; Kaliamurthy et al., 2011; Karsten et al., 2012; Kim et al., 2012; Kuhn and Ghannoum, 2003; Marzec et al., 1993; Pagiotti et al., 2011; Ribes et al., 2000; Sharma et al., 2013; Sorenson, 1999; van de Sande, 2013; Walshe and English, 1966).*

Genus/species	Disease
Aspergillus spp.	brain abscess, deep cutaneous mycosis, keratitis, mycetoma
Aspergillus flavus	keratitis, mycetoma, mycotoxins, primary cutaneous aspergillosis
Aspergillus fumigatus	allergic asthma, keratitis, mycetoma, mycotoxins, primary cutaneous aspergillosis
Aspergillus niger	asthma, brain abscess, keratitis
Aspergillus ochraceus	mycotoxins, osteomyelitis
Aspergillus repens	aspergillosis
Aspergillus tamarii	primary cutaneous aspergillosis
Aspergillus versicolor	keratitis, mycotoxins, onychomycosis
Paecilomyces spp.	keratitis, mycotoxins, peritonitis
Penicillium spp.	asthma, dermatomycosis, hyalohyphomycosis, keratitis, mycotoxins, necrotizing pneumonia, onychomycosis
Penicillium aurantiogriseum	mycotoxins

TABLE 11: *Human-pathogenic Ascomycota: Sordariomycetes (Abbott et al., 1995; Burgner et al., 1998; Erbağcı et al., 2005; Fazakas, 1938; Gürcan et al., 2006; Henke et al., 2002; Horner et al., 1995; Kaliamurthy et al., 2011; Karsten et al., 2012; Kim et al., 2012; Neal et al., 2012; Pagiotti et al., 2011; Perdomo et al., 2011; Revankar and Sutton, 2010; Shivaprasad et al., 2013; Sorenson, 1999; Tucker et al., 2004; van de Sande, 2013; Walshe and English, 1966).*

Ordo/ Familia	Genus/ species	Mycose
Hypocreales		
Clavicipitaceae	*Lecanicillium* spp.	keratitis, wound cutaneous mycosis
	Lecanicillium attenuatum, L. lecanii	wound cutaneous mycosis
	Metarhizium anisopliae	deep mycosis, keratitis, sinusitis
	Metarhizium spp.	keratitis
Cordycipitaceae	*Beauveria bassiana*	dermatomycosis, empyema, keratitis
	Beauveria brongniartii	deep mycosis
Hypocreaceae	*Acrostalagmus* spp.	keratitis
Nectriaceae	*Calonectria* spp.	allergy
	Fusarium spp.	allergy, deep cutaneous mycosis, hyalohyphomycosis, keratitis, mycetoma, mycotoxins, onychomycosis
Ophiocordycipitaceae	*Purpureocillium lilacinum*	superficial and deep mycoses
Sordariales		
Chaetomiaceae	*Chaetomium* spp.	cerebral mycosis, dermatomycosis, endocarditis, keratitis

their diseases reported only sporadically, suggesting an equilibrium between fungus and host (Pagiotti et al., 2011).

The present data originated largely from wild-caught animals. When these animals are farmed, a mycobiome shift can be expected, because farming surfaces also have a specific fungal community, and the interactions of these different communities and their implications have not been studied yet.

From the authors' point of view, two important factors should be considered in the future, when insect production is taken on a commercial level:

- Insects are a perishable good. Thus, adequate storage must be guaranteed, particularly because fungi are already present on insects physiologically or because of the rearing system.
- Food safety monitoring does attend 'fungi and yeasts' and may also analyse food samples for mycotoxins. Because of the fungi's fundamental role in arthropod physiology, it will be necessary to refine diagnostic methods to a genus level minimum. In view of the reports of the pathogenic potential of fungi considered previously inoffensive, this practice should be extended to all foodstuffs, particularly to those which are stored for a longer time.

As with bacteria, the consumption of raw insects as proposed must be discouraged until more data will be available, despite calls in popular literature (Comby, 1994; Ramos and Menzel, 1998) claim otherwise.

TABLE 12: *Human-pathogenic Ascomycota: Saccharomycetes, order Saccharomycetales (Horner et al., 1995; Karsten et al., 2012; Kennedy et al., 1972; Kim et al., 2012; Walshe and English, 1966).*

Familia	Genus/species	Disease
Metschnikowiaceae	*Metschnikowia pulcherrima*	mycetoma
Saccharomycetaceae	*Saccharomyces* spp.	keratitis
	Saccharomyces cerevisiae	allergy
(incertae sedis)	*Candida* spp.	deep cutaneous mycosis, keratitis, onychomycosis
	Candida albicans	allergy, keratitis, onychomycosis

TABLE 13: *Human-pathogenic Zygomycota (Burgner et al., 1998; Desai et al., 2013; El-Shabrawi and Kamal, 2011; Gilbert et al., 1970; Hata et al., 2008; Horner et al., 1995; Karsten et al., 2012; Khan et al., 2001; Kwon-Chung, 2012; Mendirattaet al., 2012; Ribes et al., 2000; Sorenson, 1999).*

Ordo/ Familia	Genus/ species	Mycose
Entomophthorales		
Ancylistaceae	*Conidiobolus coronatus*	fungaemia, lymphangitis, sinusitis zygomycosis
Basidiobolaceae	*Basidiobolus ranarum*	hard palate ulcerations, gastrointestinal basidiobolomycosis/zygomycosis, retroperitonitis, (sub)cutaneous zygomycosis
Entomopthoraceae	*Entomophthora* spp.	deep phycomycosis
Mucorales		
Mucoraceae	*Mucor* spp.	cerebral mycosis, endocarditis, (wound) cutaneous mycosis, gastrointestinal mycosis, keratitis, myonecrosis, onychomycosis, otomycosis, peritonitis, pulmonary mycosis, rhinocerebral mycosis, rhino-orbital mycosis, septic arthritis
	Mucor hiemalis	subcutaneous zygomycosis
Rhizopodaceae	*Rhizopus* spp.	allergy, deep mycosis, gangrene, gastrointestinal mycosis, keratitis, mastitis, mycotoxins, pulmonary mycosis, rhinocerebral mycosis, (sub)cutaneous mycosis, 'woodcutter's disease', (wound) zygomycosis

Conclusion

There is a very complex community of fungi subsisting with edible arthtropods. Some of them have the potential of being zoonotic, moreover if immune depressed patients are involved. However, these risks can be overcome by applying good manufacture practices and state-of-the-art methods to ensure food safety.

Acknowledgements

The authors wish to express their gratitude to Dr. Wiebke Jansen, formerly LMQS, for proof-reading the present review.

Conflict of interest

The authors report no declarations of interest.

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