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Reviewing the world's edible mushroom species: A new evidence-based classification system

Huili Li[1,2,3] | **Yang Tian**[4] | **Nelson Menolli Jr**[5,6] | **Lei Ye**[1,2,3] | **Samantha C. Karunarathna**[1,2,3] | **Jesus Perez-Moreno**[7] | **Mohammad Mahmudur Rahman**[8] | **Md Harunur Rashid**[8] | **Pheng Phengsintham**[9] | **Leela Rizal**[10] | **Taiga Kasuya**[11] | **Young Woon Lim**[12] | **Arun Kumar Dutta**[13] | **Abdul Nasir Khalid**[14] | **Le Thanh Huyen**[15] | **Marilen Parungao Balolong**[16] | **Gautam Baruah**[17] | **Sumedha Madawala**[18] | **Naritsada Thongklang**[19,20] | **Kevin D. Hyde**[19,20,21] | **Paul M. Kirk**[22] | **Jianchu Xu**[1,2,3] | **Jun Sheng**[23] | **Eric Boa**[24] | **Peter E. Mortimer**[1,3]

[1] CAS Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, Yunnan, China

[2] East and Central Asia Regional Office, World Agroforestry Centre (ICRAF), Kunming, Yunnan, China

[3] Centre for Mountain Futures, Kunming Institute of Botany, Kunming, Yunnan, China

[4] College of Food Science and Technology, Yunnan Agricultural University, Kunming, Yunnan, China

[5] Núcleo de Pesquisa em Micologia, Instituto de Botânica, São Paulo, Brazil

[6] Departamento de Ciências da Natureza e Matemática (DCM), Subárea de Biologia (SAB), Instituto Federal de Educação, Ciência e Tecnologia de São Paulo (IFSP), São Paulo, Brazil

[7] Colegio de Postgraduados, Campus Montecillo, Texcoco, México

[8] Global Centre for Environmental Remediation (GCER), Faculty of Science, The University of Newcastle, Callaghan, NSW 2308, Australia

[9] Biology Department, National University of Laos, Lao PDR

[10] The University of Queensland, School of Biological Sciences, Brisbane, Queensland, Australia

[11] Department of Biology, Keio University, Yokohama, Kanagawa, Japan

[12] School of Biological Sciences and Institute of Microbiology, Seoul National University, Seoul, Korea

[13] Department of Botany, West Bengal State University, Barasat, West Bengal, India

[14] Department of Botany, University of the Punjab, Lahore, Pakistan

[15] Department of Toxicology and Environmental Monitoring, Faculty of Environment, Hanoi University of Natural Resources and Environment, Tu Liem North District, Hanoi, Vietnam

[16] Department of Biology, College of Arts and Sciences, University of the Philippines, Manila, the Philippines

[17] Balipara Tract and Frontier Foundation, Guwahati, Assam, India

[18] Department of Botany, Faculty of Science, University of Peradeniya, Peradeniya, Sri Lanka

[19] Center of Excellence in Fungal Research, Mae Fah Luang University, Chiang Rai, Thailand

[20] School of Science, Mae Fah Luang University, Chiang Rai, Thailand

[21] Mushroom Research Foundation, Chiang Mai, Thailand

[22] Biodiversity Informatics and Spatial Analysis, Jodrell Laboratory, Royal Botanic Gardens Kew, Surrey, UK

[23] Key Laboratory for Agro-biodiversity and Pest Control of Ministry of Education, Yunnan Agricultural University, Kunming, China

[24] Institute of Biology, University of Aberdeen, Aberdeen, UK

Correspondence
Peter E. Mortimer, Centre for Mountain Futures, Kunming Institute of Botany, Kunming 650201, Yunnan, China.
Email: peter@mail.kib.ac.cn;
Eric Boa, Institute of Biology, University of Aberdeen, United Kingdom.
Email: e.boa@abdn.ac.uk;
Jun Sheng, Key Laboratory for Agro-biodiversity and Pest Control of Ministry of Education, Yunnan Agricultural University, Kunming, 650201, China.
Email: shengjunpuer@qq.com;
Jianchu Xu, Center for Mountain Futures, Kunming Institute of Botany, Kunming 650201, Yunnan, China.
Email: jxu@mail.kib.ac.cn;
Nelson Menolli Jr, Núcleo de Pesquisa em Micologia, Instituto de Botònica, Av. Miguel Stefano 3687, Êgua Funda, São Paulo, SP 04301-012, Brazil.
Email: menollijr@yahoo.com.br

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Abstract

Wild mushrooms are a vital source of income and nutrition for many poor communities and of value to recreational foragers. Literature relating to the edibility of mushroom species continues to expand, driven by an increasing demand for wild mushrooms, a wider interest in foraging, and the study of traditional foods. Although numerous case reports have been published on edible mushrooms, doubt and confusion persist regarding which species are safe and suitable to consume. Case reports often differ, and the evidence supporting the stated properties of mushrooms can be incomplete or ambiguous. The need for greater clarity on edible species is further underlined by increases in mushroom-related poisonings. We propose a system for categorizing mushroom species and assigning a final edibility status. Using this system, we reviewed 2,786 mushroom species from 99 countries, accessing 9,783 case reports, from over 1,100 sources. We identified 2,189 edible species, of which 2,006 can be consumed safely, and a further 183 species which required some form of pretreatment prior to safe consumption or were associated with allergic reactions by some. We identified 471 species of uncertain edibility because of missing or incomplete evidence of consumption, and 76 unconfirmed species because of unresolved, differing opinions on edibility and toxicity. This is the most comprehensive list of edible mushrooms available to date, demonstrating the huge number of mushrooms species consumed. Our review highlights the need for further information on uncertain and clash species, and the need to present evidence in a clear, unambiguous, and consistent manner.

KEYWORDS
edibility, foraging, mycology, poisonous mushrooms, wild foods

1 | INTRODUCTION

The earliest reports of mushroom consumption are from Spain (18,700 years ago), China (5,000 to 6,000 years ago), and Egypt (4,600 years ago) (Chang, 2006; Power, Salazar-García, Straus, Morales, & Henry, 2015; Straus, Morales, Carretero, & Marín-Arroyo, 2015; Zhang, Chen, Huang, Gao, & Qu, 2015). The exact process by which early humans identified edible mushroom species—those that were safe and suitable to eat—is unclear, but there is little doubt it was by trial and error, a common approach used for wild plants and other living things that were hunted or gathered for food. Small amounts were tentatively tasted, before smell, texture, and lack of any adverse reaction decided which mushrooms could be eaten. Other species were either ignored because they lacked taste or were difficult to digest, or actively avoided because they were toxic. The "Universal Edibility Test" published in the US Army Survival Manual FM 21–76 is a modern version of this process (Survival Use of Plants, 2020). The introduction of cooking (Yang, Belwal, Devkota, Li, & Luo, 2019) expanded what plants and mushrooms were "safe and suitable" to consume, through softening of tissues and detoxification. As Arora (1986) points out: "The only way to determine the edibility of a mushroom is to eat it."

Modern diets depend heavily on cultivated foods, yet foraging for wild plants and mushrooms is still widespread, both of necessity and for pleasure. The traditional knowledge of rural and indigenous communities remains a historically significant source of knowledge on edibility of wild mushrooms. Ethnomycological studies from around the world continue to document which species are considered edible and poisonous. Notable examples by region include Africa (Buyck, 2008; Buyck & Nzigidahera, 1995; Degreef, Malaisse, Rammeloo, & Baudart, 1997; Morris, 1984; Pegler & Piearce, 1980), Asia (Brown, 2019; Chamberlain, 1996; Fui, Saikim, Kulip, & Seelan, 2018; Kang et al., 2016; Kumar, Harsh, Prasad, & Pandey, 2017), Europe (Cai, Pettenella, & Vidale, 2011; Kasper-Pakosz, Pietras, & Łuczaj, 2016; Łuczaj, Stawarczyk, Kosiek, Pietras, & Kujawa, 2015; Pieroni, Nebel, Santoro, & Heinrich, 2005), Australia (Kalotas, 1997), North America (Álvarez-Farias, Diaz-Godinez, Téllez-Téllez, Villegas, & Acosta-Urdapilleta, 2016; de Avila, Welden, & Guzmán, 1980; Garibay-Orijel et al., 2020; Ruan-Soto, 2018), Central America (Guzmán, 2001b; Morales, Bran, & Cáceres, 2010), and South America (Fidalgo & Prance, 1976; Gamboa-Trujillo et al., 2019; Sanuma et al., 2016; Vasco-Palacios, Suaza, Castanõ-Betancur, & Franco-Molano, 2008). An increasing knowledge of how mushrooms grow has led to the cultivation of over 90 species (Boa, 2004), of which around 30 are grown commercially for food and consumed widely (Chang & Miles, 2004). The remaining cultivated species are grown for medicinal purposes (Lu, Lou, Hu, Liu, & Chen, 2020; Ma et al., 2018; Roncero-Ramos & Delgado-Andrade, 2017; Yang, Belwal, Devkota, Li, & Luo, 2019), as functional foods (Jabłońska-Ryś, Skrzypczak, Sławińska, Radzki, & Gustaw, 2019; Reis, Martins, Vasconcelos, Morales, & Ferreira, 2017) and extracts used as food additives (Hadar & Dosoretz, 1991; Sun et al., 2020).

The overall result is that mushroom consumption has risen 21-fold over the last 56 years (Food and Agriculture Organization Statistical, 2017). Harvesting of wild mushrooms, the vast majority of which cannot be cultivated, remains hugely important, both as a source of food and income (Boa, 2004; Hall, Buchanan, Cole, Yun, & Stephenson, 2003). The first significant attempt to list edible species from around the world was by Chandra (1989). She listed 628 edible mushroom species, with notes on taste and how to prepare before eating. An extensive global review of the literature, including gray literature and personal contacts, by Boa (2004) identified 2166 edible mushroom species collected across 85 countries. Peintner et al. (2013) listed 268 wild mushroom species of commercial importance from 27 European countries. Wu et al. (2019) list 1,020 edible mushroom species and 480 poisonous mushroom species from China. Some authors note edible species that contain toxins when raw and require pretreatment before safe consumption is possible (Niksic, Klaus, & Argyropoulos, 2016). The published information on edible properties varies considerably, however, with field guides intended for a wider, non-academic readership, providing much more detail.

Interest in edible mushrooms continues to grow as the demand for new types of food increases and alternative sources of income for rural communities are sought (Pilz & Molina, 2002). In Asia, Europe and North America more people than ever are "foraging," reviving mushroom traditions diluted by migrations to cities and creating new challenges for sustainable production (Egli, Peter, Buser, Stahel, & Ayer, 2006). Harvesting wild species of commercial importance, such as matsutake (*Tricholoma* spp.), boletes (*Boletus* spp.), truffles (*Tuber* spp.), morels (*Morchella* spp.), and various *Lactarius* species (e.g., *L. deliciosus*), is big business in many countries and essential income for collectors and their families (Boa, 2004; de-Román & Boa, 2006; Yeh, 2000).

Regular reports of mushroom poisoning continue to occur. There is no evidence to suggest that the frequency of such reports has significantly increased on a global scale, but there is little doubt that the greater ease of sharing information through social media and the internet has heightened concerns about the danger of eating wild mushrooms. Govorushko, Rezaee, Duanov, and Tsatsakis (2019) report that between 200 and 250 people are poisoned by mushrooms each year. Furthermore, Chen, Ping, and Zhang (2014) reported that between the years 2000 and 2014, there were 1,954 poisoning cases and 409 deaths related to mushroom use in China.

Reports on edible and poisonous mushrooms appear regularly in many different publications, including peer-reviewed papers, field guides, newsletters of mycological and nature societies, and "gray literature," such as project reports and informal publications. A plethora of websites offer opinions on what mushrooms to eat and what to avoid yet reports are often inconsistent and contradictory. Opinions vary on the culinary merits of a species, but, more importantly, on what species can be eaten and which ones are poisonous. These disagreements occur partly because of different cultural attitudes and biases (Härkönen, 2002), but also because of the degree of risk people are willing to accept, which is often tied to the depth of knowledge regarding the use of wild mushrooms. Those with a rich tradition of eating mushrooms from the wild are often more adventurous in the species they will eat. Where this tradition is weak or absent, fewer species from the wild are consumed, and there is an increased tendency to label species as "inedible," "avoid," or "suspect." Such terms imply potential toxicity, yet Shernoff (2015) suggested that many species labeled as "inedible" in US field guides were harmless.

In an attempt to distinguish reports that showed clear evidence of a species having been consumed (either by the author(s) or reliable cited source), Boa (2011) separated "food" species from "edible" species, with an additional category for poisonous species. These categories were an attempt to standardize reports on properties and to enable comparisons from different sources. It was also an attempt to emphasize the quality of evidence presented for a report and therefore the reliability of the report.

The most reliable reports on edibility are those that provide evidence of consumption, which could include personal experiences of authors or those of colleagues (e.g., Arora, 1986) or cited sources (e.g., Chandra, 1989). A surprising number of peer-reviewed publications do not give the source of evidence, as discussed by Rubel and Arora (2008). No source is given for the 1,323 edible species reported from China (Wu et al., 2019), for example. Field guides written for naturalists and foragers are a rich source of first-hand information on a wide range of edible and poisonous species, often over a large physical area (e.g., Rodríguez et al., 1999; Tudor, 2010; Wang, Liu, & Yu, 2004). Ethnomycology studies provide in-depth local knowledge on edible mushrooms for a defined region (Brown, 2019; Comandini & Rinaldi, 2020).

The increasing interest in foraging and the commercial importance of edible mushrooms collected from the wild emphasize the need for reliable information on the properties of species. Medical staff need accurate information on properties to diagnose cases of suspected mushroom poisonings. There is also a wider imperative to ensure that consumers understand any risks associated with edible species, such as the need to prepare in a particular way or avoid consuming with alcohol. Current confusions and disagreements about the properties of edible mushrooms gathered from the wild limits their potential both as food and a source of income. Of the 2,166 edible mushrooms listed in Boa (2011), 589 species recorded as edible lacked clear and credible evidence of consumption.

The uncertainty surrounding the edibility of a significant number of mushroom species and the need for consistent reporting has prompted the current review of published case reports from around the world. This paper describes an evidence-based approach for weighing up published information and establishing greater clarity of current knowledge on the edibility of wild mushrooms.

2 | DATA RESOURCES UTILIZED IN THE REVIEW PROCESS

Extensive search was carried out in peer-reviewed publications, field guides, books, conference proceedings, project reports, and other information available on the web or from personal knowledge of mycologists for information concerning the edibility of mushroom species. Each record of a species property is referred to here as a case report. We included two records of slime molds in our list of edible mushrooms (*Fuligo septica* var. *septica* and *Reticularia lycoperdon*) as these have been considered as edible fungi in the past, and many collectors of wild fungi still treat them accordingly. The original records varied in length from one-word labels to more detailed discussions of properties.

This study builds on an original summary of case reports that appeared in Boa (2004), updated to include information from new sources published up to April 2020. The earliest source of case reports is from a 1849 publication by Lindley (Lindley, 1849). The complete data set contains 9,783 case reports from 99 countries and over 1,100 sources. We incorporated the following languages in our search: Bengali, Bhutanese, Burmese, English, Filipino, Japanese, Korean, Laotian, Malayalam, Mandarin, Nepali, Portuguese, Russian, Spanish, Tamil, Thai, Vietnamese, and Urdu. Scientific names follow indexfungorum.org (Index Fungorum, 2020) and speciesfungorum.org (Species Fungorum, 2020). Current names are used and spelling errors that occurred in the case reports have been corrected. The published scientific names used in the case reports appear in Supporting Information Table S1 together with their current names.

3 | SYSTEM FOR CATEGORIZING MUSHROOM EDIBILITY

Boa (2004) assigned case reports to a series of categories defining the key characteristics of mushrooms and, crucially, distinguishing between reports which provided clear evidence of consumption. The original scheme has been simplified (Table 1) and four categories have been used to classify all case reports analyzed based on available information: edible (E1); edible with conditions (E2); edible, unconfirmed (E3); and poisonous (P).

The advantage of this classification is that it enables a cross-comparison of case reports from different sources and establishes a consistent approach for determining the final edibility status (FES) of a species. The disadvantage of using the four categories listed in Table 1 is that the finer details of extended case reports are lost, including comments on taste and texture and possible toxicity to people. Taste and texture are subjective features and are not part of the current analysis. Where information is unclear, ambiguous or missing, case reports are assigned to category E3. This category may also include species which are safe to eat but are deemed unsuitable because of taste, smell, texture or some other feature that people find undesirable. Such species were often described as "inedible." Rubel and Arora (2008) explain how lack of awareness of different cultural attitudes and practices has influenced and distorted the perception of *Amanita muscaria* as a highly poisonous mushroom, despite the fact that it can, with suitable treatment, be safely consumed.

Almost half of the 2,786 species we report on had only one case report (Table 3). This becomes the *de facto* FES. For the remaining species, we separated those with consistent case reports from those with mixed case reports (Figure 1), which were then assessed and given an FES based on a "summary judgement" (Table 2). Note that all species with a combination of at least one poisonous and at least one E1, E2, or E3 case report were given an

TABLE 1 Edibility categories (E1, E2, E3, and P) assigned to classify reported properties of mushrooms

Edibility category	Code	Description
Edible, confirmed	E1	Clear evidence that a species has been consumed without adverse or harmful effects and is safe and suitable to eat
Edible, confirmed but with conditions	E2	Clear evidence that a species has been consumed after it has been cooked or prepared in such a way as to make it safe and suitable to eat. Includes species that may result in allergic or adverse reactions when consumed with alcohol, for example
Edible, unconfirmed	E3	Evidence of safe consumption is uncertain or incomplete
Poisonous	P	Causes adverse and harmful reactions when consumed

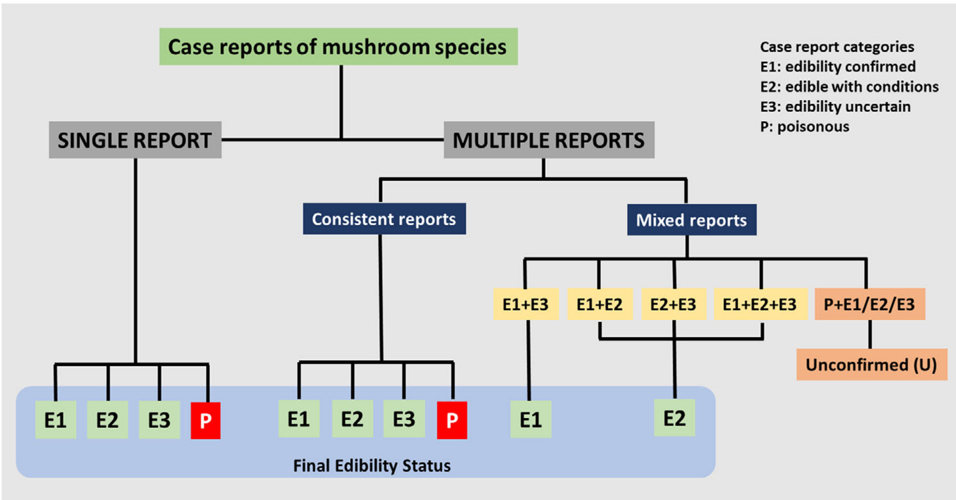

FIGURE 1 Flow chart for determination of final edibility status

"unconfirmed" (U) FES. These U species were then given an additional level of scrutiny by the authors, being reviewed and classified as E1, E2, or P depending on the balance and strength of the available evidence. For example, a U species sold at a market provided compelling evidence that it was edible. When no FES could be made using reliable evidence, the status remained U, an indication that further research is required to clarify the edibility of these species. Species with mixed case reports of E3 and P only were described as poisonous (Table 2).

TABLE 2 Assessing the final edibility status of mushrooms with differing (mixed) case reports

Combination of case reports	Final edible status	Notes
E1 and E2	E2	
E2 and E3	E2	
E1 and E3	E1	
E1, E2 and E3	E2	
P and E3 only	E3	
P and E1, E2 or E3 or combination	U (unconfirmed)	Species were reclassified (E1, E2, or P) if supported by the balance of evidence contained in case reports

The number of consistent case reports obtained indicates the general strength of the supporting evidence. This strength is also, however, related to the number of people who have eaten a mushroom of a particular species without ill-effect, information that varied considerably in the original source or was simply missing. No distinction was made between case reports that described varying degrees or intensity of adverse reactions to consumption of poisonous species. Accordingly, the poisonous category includes species described as mildly poisonous, potentially lethal or deadly, or other variations on a toxic theme. All reports of poisonous species were taken at face value, regardless of the strength of the supporting evidence.

Consistent efforts were made to obtain at least two case reports for each species and to ensure that these were from different countries or major regions within larger

TABLE 3 Final edibility status of 2,786 mushrooms based on an analysis of 9,783 case reports from 99 countries

Final edibility status (FES)	Taxa	One case report	More than one case report, consistent	More than one case report, mixed
E1: edibility confirmed	2,006	964	692	350
E2: edible but with conditions	183	16	0	167
E3: edibility uncertain	471	453	16	2
P: poisonous	50	0	0	50
U: unconfirmed	76	0	0	76
Total	**2,786**	**1,433**	**708**	**645**

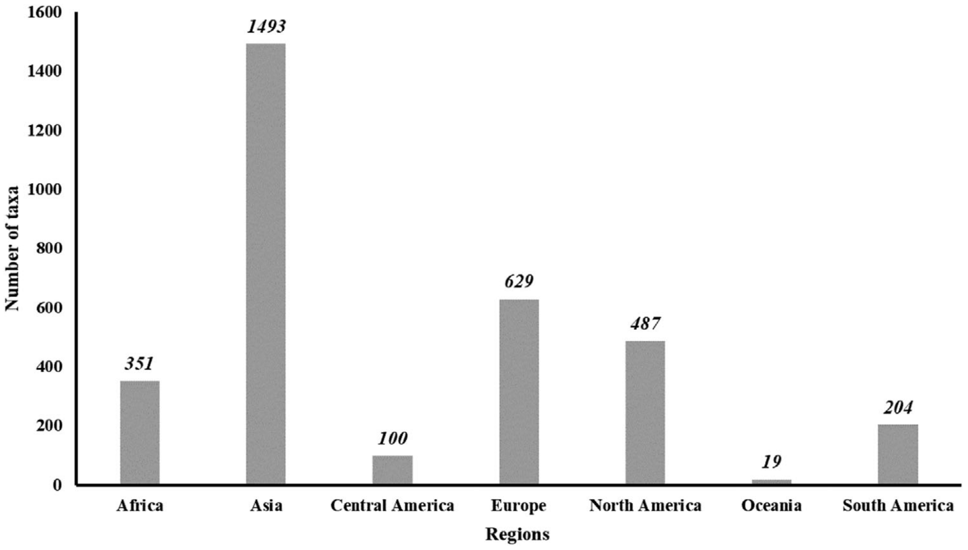

FIGURE 2 Final edibility status of E1 and E2 taxa from different regions

countries. This was often not possible, as noted in the results and discussed later in this paper. We did not systematically attempt to document all ostensibly poisonous species. Sources of information on edible mushrooms usually contained case reports of poisonous species, but it was clear that lists were often incomplete. Laessøe and Petersen (2019) list 112 poisonous species for temperate Europe that are not yet included in our data set, for example.

Further information and wider evaluation are required for those species with mixed case reports, especially those with conflicting reports of edibility and toxicity. In addition to giving extra weight to those species sold in markets when reviewing U species, we also looked carefully at first-hand information provided in a number of key sources from different regions: North America (e.g., Arora, 1986; McIlvaine & Macadam, 1900; Pérez-Moreno, Lorenzana-Fernández, Carrasco-Hernández, & Yescas-Pérez, 2010; Villarreal & Perez-Moreno, 1989a), Europe (e.g., Afonkin, 2013; Papetti, Consiglio, & Simonini, 2017), and Asia (e.g., Adhikari, 2000; Wang, Liu, & Yu, 2004).

4 | OVERVIEW OF WORLD'S EDIBLE MUSHROOMS

We report on the properties of 2,786 taxa, including four forms, two subspecies, and one variety (Table 3), obtained from 9,783 case reports (the source of individual case reports is shown in Supporting Information SI). We obtained case reports of wild mushroom species from 33 countries in Africa, 26 from Asia, 20 from Europe, 18 from the Americas, and two from Oceania. The highest number of edible mushroom species (E1 and E2) were reported in Asia (1,493), followed by Europe (629), North America (487), Africa (351), South America (204), Central America (100), and Oceania (19) (Figure 2). There are 614 edible mushroom species (E1 and E2) found on two or more continents.

The vast majority of species (72%) had an FES of E1, that is those mushrooms with clear evidence of being safe and suitable to eat. This group included 350 (17%) taxa with an FES of E1 which had mixed case reports, mainly "confirmed" and "uncertain or incomplete" edibility. Concrete

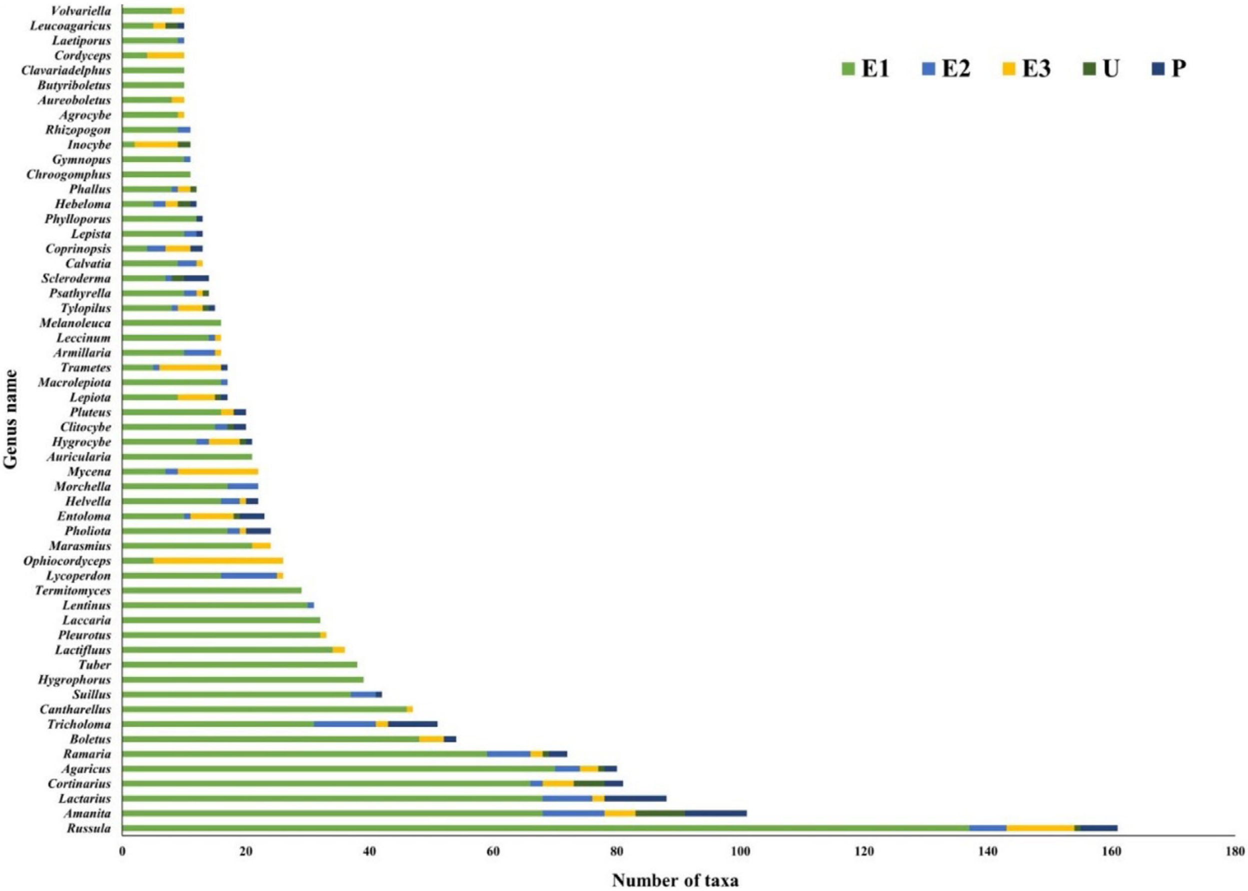

FIGURE 3 The number of taxa from genera with 10 or more case reports and their final edibility status. E1: confirmed edible; E2: edible with conditions; E3: uncertain; U: unconfirmed edible; P: poisonous

evidence of consumption here carries most weight. A lack of evidence does not mean that a species cannot be eaten or is poisonous. It may simply indicate that a species is not eaten in a particular place.

Of the 230 taxa originally classified as "unconfirmed," a small but notable number of taxa (76) could not be reclassified (Table 3) because of unresolved clashes on reported properties. A total of 154 taxa with contradictory evidence on safe consumption were reclassified, of which 28 taxa were given an FES of E1 after consulting reliable sources of evidence (Table 4), and 76 taxa given an FES of E2. Precedence was given in mixed case reports to at least one stating preconditions for consumption or allergic reactions.

The sum of taxa with an FES of E3 or U accounts for 20% of all the taxa recorded in our review of global sources, and further research is needed to decide whether these are edible or poisonous. The majority of taxa with an FES of E3 had only one case report. The depth of reporting on the properties of taxa with an FES of E1 and E2 is also weak, with 908 species, 35% of the combined taxa, represented by one case report.

Data on the FES of species from major genera with 10 or more taxa are shown in Figure 3 and Supporting Information Table S2. *Russula* had the greatest number of recorded species (161), with 143 confirmed as edible (E1 or E2), 11 as E3, one as P, and six of unconfirmed FES. *Amanita* had the second highest number of taxa (100 species and 1 forma specialis), including 78 edible taxa (E1 or E2), 5 as E3, 8 as P, and 10 species of unconfirmed FES. *Lactarius* was third with 88 species, comprising 76 edible species (E1 or E2), 2 as E3, and 10 species as U. Nine genera contained only confirmed edible species (E1 or E2): *Auricularia* (21 spp.), *Butyriboletus* (10 spp.), *Chroogomphus* (11 spp.), *Clavariadelphus* (10 spp.), *Hygrophorus* (39 spp.), *Laccaria* (32 spp.), *Melanoleuca* (16 spp.), *Termitomyces* (29 spp.), and *Tuber* (38 spp.).

We calculated the number of edible species (FES of E1 or E2) for major genera as a proportion of all the species shown in speciesfungorum.org (Species Fungorum, 2020). Although *Russula* had the highest number of edible species, these represented only 11% of all species (1322 spp.). The same proportion of edible species was found for *Amanita* (Supporting information Table S2 & S3). Edible species of *Auricularia*, *Retiboletus*, *Sparassis*, and *Termitomyces* represent more than 50% of all the species recorded in speciesfungorum.org. *Entoloma* and *Inocybe*

TABLE 4 Revised final edibility status of 154 taxa with mixed case reports, including at least one poisonous, and originally classified as U (unconfirmed) *. E1: Edibility confirmed; E2: Edibility with conditions; E3: Edibility uncertain; P: Poisonous

	Number of case reports						
Taxa	**E1**	**E2**	**E3**	**P**	**All**	**Final edibility status (FES)**	**Source(s) used to revise FES**
Agaricus abruptibulbus	2	0	0	1	3	E2	(Arora, 1986; Zhou & Zhang, 2005)
Agaricus arvensis	27	0	2	1	30	E2	(Afonkin, 2013; Arora, 1986)
Agaricus phaeolepidotus	0	0	1	1	2	P	
Agaricus semotus	3	0	2	1	6	E1	(Afonkin, 2013)
Agaricus sylvicola	24	0	2	1	27	E2	(Afonkin, 2013; Arora, 1986; McIlvaine & Macadam, 1900)
Amanita castanopsidis	0	0	1	2	3	P	
Amanita citrina	1	0	2	8	11	P	(Bresinksy & Bresl, 1990)
Amanita excelsa	4	2	2	3	11	E2	(McIlvaine & Macadam, 1900)
Amanita flavipes	0	0	1	1	2	P	
Amanita fuliginea	0	0	1	4	5	P	
Amanita ovoidea	3	0	0	2	5	E1	(Afonkin, 2013; Papetti et al., 2017)
Amanita porphyria	0	0	2	5	7	P	
Amanita pseudogemmata	0	0	1	2	3	P	
Amanita pseudoporphyria	2	0	0	5	7	E2	(Afonkin, 2013; Wang et al., 2004)
Amanita rubrovolvata	0	0	1	4	5	P	
Amanita rufoferruginea	0	0	1	4	5	P	
Amanita vaginata	19	4	10	2	35	E2	(Afonkin, 2013; Arora, 1986)
Ampulloclitocybe clavipes	7	4	2	1	14	E2	(Afonkin, 2013; Arora, 1986; McIlvaine & Macadam, 1900)
Astraeus hygrometricus	7	1	1	1	10	E2	(Afonkin, 2013; Arora, 1991)
Baorangia pseudocalopus	1	0	0	2	3	P	(Li et al., 2019)
Bolbitius titubans	0	0	1	4	5	P	
Boletus sensibilis	2	0	1	4	7	E1	(Wang et al., 2004)
Boletus subvelutipes	3	0	0	3	6	E1	(Rubel & Arora, 2008)
Caloboletus calopus	3	0	1	6	10	E2	(Wang et al., 2004)
Chlorophyllum molybdites	5	0	1	21	27	E2	(Arora, 1986)
Chlorophyllum rhacodes	19	2	0	2	23	E2	(Afonkin, 2013)
Clathrus archeri	2	0	0	2	4	E2	(Arora, 1986)

(Continues)

TABLE 4 (Continued)

Taxa	Number of case reports					Final edibility status (FES)	Source(s) used to revise FES
	E1	E2	E3	P	All		
Clavariadelphus pistillaris	8	1	1	2	12	E1	(Arora, 1986)
Clitocybe dealbata	1	0	0	11	12	P	(Afonkin, 2013; Papetti et al., 2017)
Clitocybe fragrans	3	0	1	4	8	E2	(McIlvaine & Macadam, 1900)
Clitocybe nebularis	14	4	2	3	23	E2	(Afonkin, 2013; Arora, 1986; Zhou & Zhang, 2005)
Clitocybe phyllophila	2	0	1	11	14	P	(Afonkin, 2013)
Clitocybe rivulosa	0	0	1	6	7	P	
Conocybe apala	0	0	1	3	4	P	
Conocybe tenera	0	0	1	2	3	P	
Coprinellus micaceus	5	6	3	1	15	E2	(Arora, 1986)
Coprinopsis atramentaria	11	6	2	6	25	E2	(Afonkin, 2013; Arora, 1986; Zhou & Zhang, 2005)
Coprinopsis picacea	1	0	0	1	2	E2	(Arora, 1986; McIlvaine & Macadam, 1900)
Coprinus comatus	31	3	4	1	39	E1	(Afonkin, 2013; Arora, 1986)
Cortinarius bolaris	0	0	1	1	2	P	
Cortinarius cinnamomeus	4	0	0	4	8	E2	(McIlvaine & Macadam, 1900)
Cortinarius gentilis	0	0	1	1	2	P	
Cortinarius sanguineus	0	0	1	4	5	P	
Cortinarius semisanguineus	0	0	1	2	3	P	
Cortinarius traganus	0	0	1	2	3	P	
Cyanoboletus pulverulentus	8	0	0	2	10	E1	(Afonkin, 2013; Papetti et al., 2013)
Deconica merdaria	0	0	1	2	3	P	
Dictyophora multicolor	1	0	0	1	2	E2	(Arora, 1986)
Entoloma omiense	0	0	1	2	3	P	
Entoloma rhodopolium	1	0	1	14	16	P	(Afonkin, 2013)
Entoloma vernum	1	0	0	4	5	P	(Afonkin, 2013)
Gliophorus psittacinus	2	0	1	1	4	E2	(McIlvaine & Macadam, 1900)
Gymnopilus aeruginosus	0	0	1	3	4	P	
Gymnopilus junonius	2	2	0	8	12	E2	(Afonkin, 2013; Deschamps, 2002)
Gyromitra esculenta	3	3	5	13	24	E2	(Afonkin, 2013; Arora, 1986)
Gyromitra gigas	3	1	0	5	9	E2	(Afonkin, 2013; Arora, 1986)

(Continues)

TABLE 4 (Continued)

Taxa	Number of case reports					Final edibility status (FES)	Source(s) used to revise FES
	E1	E2	E3	P	All		
Gyroporus castaneus	11	0	4	1	16	E1	(Arora, 1986; Zhou & Zhang, 2005)
Hebeloma fastibile	2	0	0	1	3	E2	(Pérez-Moreno, Martínez-Reyes, Yescas-Pérez, Delgado-Alvarado, & Xoconostle-Cázares, 2008)
Hebeloma mesophaeum	1	0	0	1	2	E2	(Pérez-Moreno et al., 2008)
Hebeloma sacchariolens	0	0	1	1	2	P	
Hebeloma sinapizans	0	0	1	3	4	P	
Helvella acetabulum	7	0	0	1	8	E1	(Montoya-Esquivel, Estrada-Torres, Kong, & Juarez-Sanchez, 2001)
Helvella crispa	19	0	0	2	21	E2	(McIlvaine & Macadam, 1900; Pérez-Moreno et al., 2008)
Helvella elastica	8	0	2	2	12	E2	(McIlvaine & Macadam, 1900; Pérez-Moreno et al., 2008)
Helvella lacunosa	18	1	2	2	23	E2	(Arora, 1986; Pérez-Moreno et al., 2008)
Hygrocybe nigrescens	1	0	1	2	4	E2	(Pérez-Moreno et al., 2008)
Hygrocybe ovina	0	0	1	1	2	P	
Hygrocybe punicea	8	0	2	1	11	E2	(Arora, 1986)
Hygrophoropsis aurantiaca	9	1	3	1	14	E2	(Arora, 1986)
Hypholoma capnoides	8	0	1	1	10	E2	(Arora, 1986; McIlvaine & Macadam, 1900)
Imleria badia	20	0	3	1	24	E2	(Arora, 1986; McIlvaine & Macadam, 1900)
Imperator rhodopurpureus	0	1	0	2	3	E2	(McIlvaine & Macadam, 1900)
Infundibulicybe gibba	15	0	1	1	17	E2	(Arora, 1986; Pérez-Moreno et al., 2008)
Inocybe flavobrunnea	0	0	1	2	3	P	
Inocybe geophylla	0	0	1	7	8	P	

(Continues)

TABLE 4 (Continued)

Taxa	Number of case reports E1	E2	E3	P	All	Final edibility status (FES)	Source(s) used to revise FES
Inonotus obliquus	2	0	1	1	4	P	
Lactarius piperatus	17	2	3	1	23	E2	(Arora, 1986; Zhou & Zhang, 2005)
Lactarius pubescens	6	0	1	2	9	E1	(Afonkin, 2013)
Lactarius repraesentaneus	2	0	2	1	5	E1	(Afonkin, 2013)
Lactarius rufus	3	1	1	2	7	E1	(Afonkin, 2013)
Lactarius scrobiculatus	5	0	2	2	9	E1	(Afonkin, 2013; Papetti et al., 2017)
Lactarius torminosus	4	1	2	6	13	P	(Afonkin, 2013; Li et al., 2020; Papetti et al., 2017)
Lactarius turpis	5	0	1	1	7	E2	(McIlvaine & Macadam, 1900)
Lactarius uvidus	2	0	2	1	5	E1	(Afonkin, 2013)
Lactarius vellereus	9	0	3	1	13	E2	(McIlvaine & Macadam, 1900)
Lactarius zonarius	3	0	2	4	9	E1	(Afonkin, 2013)
Lepiota clypeolaria	2	0	3	2	7	P	(Afonkin, 2013; Papetti et al., 2017)
Lepiota cristata	0	0	1	8	9	P	
Lepista irina	8	0	2	1	11	E1	(Afonkin, 2013)
Leucoagaricus americanus	4	0	3	2	9	E2	(Afonkin, 2013; Mendoza, 1938)
Leucoagaricus badhamii	0	0	1	4	5	P	
Leucoagaricus leucothites	17	0	2	1	20	E1	(Afonkin, 2013; Papetti et al., 2017)
Leucocoprinus birnbaumii	0	0	1	3	4	P	
Leucocoprinus cepistipes	2	0	2	1	5	E2	(Afonkin, 2013; Zhou & Zhang, 2005)
Lysurus arachnoideus	0	0	1	2	3	P	
Meiorganum curtisii	0	0	1	2	3	P	
Meripilus giganteus	12	2	0	1	15	E2	(Afonkin, 2013)
Mutinus bambusinus	0	0	2	1	3	P	
Mutinus caninus	0	0	1	1	2	P	
Mycena haematopus	1	0	1	1	3	E2	(Arora, 1986)
Mycena pura	4	0	2	10	16	E2	(Arora, 1986; Zhou & Zhang, 2005)
Neoboletus erythropus	5	0	0	1	6	E2	(Arora, 1986)
Neoboletus luridiformis	11	2	3	1	17	E1	(Afonkin, 2013)
Neolentinus lepideus	9	2	0	1	12	E1	(Afonkin, 2013; McIlvaine & Macadam, 1900)

(Continues)

TABLE 4 (Continued)

Taxa	Number of case reports E1	E2	E3	P	All	Final edibility status (FES)	Source(s) used to revise FES
Omphalotus olearius	1	0	1	14	16	P	(Bresinksy & Bresl, 1990; Papetti et al., 2017)
Otidea cochleata	1	0	0	1	2	E1	(Afonkin, 2013)
Paxillus involutus	2	3	2	14	21	E2	(McIlvaine & Macadam, 1900)
Phaeolepiota aurea	8	3	1	1	13	E2	(Arora, 1986)
Phallus impudicus	11	2	1	2	16	E2	(McIlvaine & Macadam, 1900)
Phallus tenuis	0	0	1	2	3	P	
Pholiota flammans	2	0	2	1	5	E2	(Arora, 1986; McIlvaine & Macadam, 1900)
Pholiota squarrosa	6	2	2	3	13	E2	(Afonkin, 2013)
Pholiota terrestris	2	0	0	3	5	E2	(Arora, 1986)
Pluteus petasatus	5	0	0	1	6	E1	(Afonkin, 2013)
Pluteus salicinus	2	0	1	3	6	E1	(Afonkin, 2013; Papetti et al., 2017)
Protostropharia semiglobata	2	0	3	1	6	E2	(McIlvaine & Macadam, 1900)
Psathyrella corrugis	0	0	1	1	2	P	
Psilocybe coronilla	4	0	1	4	9	E2	(Pérez-Moreno et al., 2008)
Pulveroboletus ravenelii	1	0	3	2	6	E1	(Wang et al., 2004)
Ramaria flava	13	1	2	3	19	E2	(Adhikari, 2000)
Ramaria flavobrunnescens	4	0	1	1	6	E2	(Pérez-Moreno et al., 2008)
Ramaria formosa	3	0	1	14	18	E2	(Afonkin, 2013; Wang et al., 2004)
Rubroboletus satanas	1	0	0	15	16	P	(Afonkin, 2013; Arora, 1991; Papetti et al., 2017)
Russula adusta	16	1	3	3	23	E2	(McIlvaine & Macadam, 1900; Wang et al., 2004)
Russula densifolia	8	1	1	4	14	E2	(Arora, 1986; Wang et al., 2004)
Russula fellea	1	0	1	1	3	E1	(Afonkin, 2013)
Russula foetens	3	0	2	7	12	E2	(McIlvaine & Macadam, 1900)
Russula sardonia	2	0	1	1	4	P	(Afonkin, 2013)
Sarcosphaera coronaria	3	1	1	2	7	E2	(Arora, 1986)
Scleroderma cepa	1	0	0	1	2	P	(Afonkin, 2013; Li et al., 2020)
Scleroderma citrinum	4	0	3	9	16	E2	(Wang et al., 2004)
Scleroderma flavidum	2	0	0	2	4	E1	(Wang et al., 2004)

(Continues)

TABLE 4 (Continued)

Taxa	Number of case reports					Final edibility status (FES)	Source(s) used to revise FES
	E1	E2	E3	P	All		
Strobilomyces strobilaceus	10	0	1	1	12	E1	(Arora, 1986; McIlvaine & Macadam, 1900)
Stropharia aeruginosa	9	0	0	3	12	E2	(Dai, Yang, Cui, Yu, & Zhou, 2009; Zhou& Zhang., 2005)
Suillellus luridus	10	2	3	2	17	E2	(McIlvaine & Macadam, 1900)
Suillus americanus	9	0	0	2	11	E2	(Pérez-Moreno et al., 2008)
Suillus granulatus	34	3	4	1	42	E2	(Arora, 1986; Pérez-Moreno et al., 2008)
Suillus luteus	30	2	0	1	33	E2	(Arora, 1986; Pérez-Moreno et al., 2008)
Suillus placidus	8	0	1	3	12	E2	(Wang et al., 2004)
Suillus spraguei	6	1	1	1	9	E2	(Arora, 1986)
Tapinella panuoides	2	0	1	2	5	P	(Afonkin, 2013)
Trametes versicolor	5	0	1	1	7	E2	(Arora, 1986)
Tricholoma album	6	0	1	3	10	E2	(McIlvaine & Macadam, 1900)
Tricholoma equestre	24	1	1	8	34	E2	(Arora, 1986; McIlvaine & Macadam, 1900)
Tricholoma focale	2	0	0	1	3	E1	(Afonkin, 2013)
Tricholoma pessundatum	3	1	1	3	8	E2	(Arora, 1986)
Tricholoma saponaceum	1	2	2	5	10	E2	(McIlvaine & Macadam, 1900; Zhou & Zhang, 2005)
Tricholoma sejunctum	8	0	1	2	11	E2	(McIlvaine & Macadam, 1900)
Tricholoma sulphureum	2	0	0	2	4	P	(Afonkin, 2013; Papetti et al., 2017)
Tricholoma ustale	2	1	1	4	8	E2	(McIlvaine & Macadam, 1900)
Tricholomopsis rutilans	4	4	3	3	14	E2	(Arora, 1986)
Tylopilus neofelleus	0	0	1	1	2	P	
Verpa bohemica	11	2	2	1	16	E2	(Arora, 1986)
Volvopluteus gloiocephalus	23	0	2	2	27	E1	(Afonkin, 2013; Jones, Whalley, & Hywel-Jones, 1994)

*Mixed case reports comprising P and E3 only were given an FES of P.

had the lowest proportion of edible species (< 0.6%) of all species.

The species listed in our study for *Auricularia*, *Butyriboletus*, *Chroogomphus*, *Clavariadelphus*, *Hygrophorus*, *Laccaria*, *Melanoleuca*, *Termitomyces*, and *Tuber* were all considered edible in their FES, without any preconditions or uncertainties, an indication that these species are undoubtedly safe to eat. Alternatively, there are 100 *Amanita* species included in our study, representing 14% of the species in this group, with 78 (11%) species listed as confirmed edible (Species Fungorum, 2020; Zhang, Tang, Cai, & Xu, 2015). The work of Zhang et al. (2015) listed approximately 50 *Amanita* species as being edible; thus, our research updates this number. *Amanita* species should be treated with caution, as there are about 100 considered poisonous, and of these, about 50 species are considered to be deadly (Cai, Cui, & Yang, 2016), some of which could be easily confused with the edible *Amanita* species listed in our study. Similarly, although with fewer deadly species, *Russula* is another group of mushrooms to be treated with a degree of caution, as there are numerous poisonous species, often occurring alongside, and sharing similar morphologies as edible *Russula* species (143 listed in our study). Of the species listed within *Entoloma* and *Inocybe*, < 0.6% are confirmed edible species, and thus when eating mushrooms from these genera, extreme caution is recommended. Although not considered deadly to humans, there are a number of poisoning cases resulting from the consumption of *Entoloma* species (Chen, Yang, Bau, & Li, 2016; de Oliveira, 2009; Hossain & Park, 2016; Puschner, 2018; Schenk-Jaeger et al., 2012). Furthermore, *Inocybe erubescens* is considered deadly to humans, and a number of additional *Inocybe* species are poisonous, due to the presence of muscarine (Brown, Malone, Stuntz, & Tyler Jr, 1962; Lurie et al., 2009).

5 | THE IMPORTANCE OF DEVELOPING AN EVIDENCE-BASED CLASSIFICATION SYSTEM

5.1 | Assessing the viability of the evidence-based classification system

This review is the first systematic attempt to document and categorize edible mushroom species using an evidence-based approach. Much of the available information regarding species edibility is from unverified sources, word-of-mouth, or publications that have not been subject to any form of review, and it is unsurprising that reports on the edibility of a species often vary. The use of standard categories to describe case reports is an essential part of the method we have used to determine the FES of species, combined with a proposed set of rules for interpreting mixed case reports (Table 2; Figure 1).

The Universal Edibility Test is the only published method for determining which species can be safely eaten (Survival Use of Plants, 2020). There are no formal laboratory standards for establishing if a species is edible. Known toxins can be detected in mushroom species by chemical analyses (Bever et al., 2020; Bresinsky & Besl, 1990), although their presence does not preclude consumption. Cooking and other pretreatment help to destroy and eliminate poisons present in certain species of raw mushrooms, as demonstrated for *Amanita muscaria* and discussed more widely for other species by Rubel and Arora (2008).

Our review of mushroom properties has highlighted the reliance on subjective, often anecdotal, sources of information on the edibility of a mushroom, and is one possible reason why case reports differ. Our proposed classification system allows researchers and practitioners to weigh up the available evidence for a species, and then categorize the species according to a set of rules (Table 3, Figure 1). This classification system enables users to easily understand the certainty with which a mushroom can be considered edible and provides a verifiable chain of evidence for decisions made on the FES.

This review of edible mushrooms is a work in progress, and our list of edible species and related judgments on FES are likely to change and be updated as new evidence is presented. One of the challenges we faced when determining the FES of a species was the limited number of case reports showing direct evidence of consumption. We hope that in the future, this situation will be improved upon and that subsequent judgements will be more robust as a result. The classification system will need further testing and discussions to ensure that it is fit for purpose and to encourage wider adoption of a standard method for confirming and categorizing the edibility of species and the strength of the supporting evidence.

We have identified 2,189 edible mushroom species (FES = E1 or E2), a slight increase in the 2,166 edible species reported by Boa (2004), despite the greater number of species analyzed and case reports used in the current study. However, we have also identified 471 species of unknown edibility (E3), of which a substantial proportion could be reclassified once additional information is made available.

With the exception of the E3 group, we speculate that it is unlikely that there are many more edible species of value to be documented. We also acknowledge that limitations of our review based on the literature that was available for this analysis. The majority of species within *Auricularia*, *Retiboletus*, *Sparassis*, and *Termitomyces* were found to be edible, yet there are other species less well known and regions where published information on mushroom properties is limited. It is likely that all species of *Lentinula* and *Pleurotus* are in fact edible but there is no current documentation confirming this. We speculate that all mushroom species from a genus such as Tuber are edible, though of varying value by taste.

We estimate that there are about 27,000 mushroom species (Hawksworth, 2001; Cannon et al., 2018), of which our review shows about 10% to be edible. According to the estimates of Hawksworth and Lücking (2017), many unknown mushroom species have yet to be documented, and though we can expect a high number of new edible species to be discovered, their value as food remains to be confirmed. Documenting these new species and determining the edibility of them will take generations of mycologists, incorporating studies on taxonomy, ecology, ethnomycology, and pharmacology.

5.2 | Distribution of wild edible mushrooms

The number of case reports by species and country varied hugely with a strong bias toward countries with a well-established research community, not only in mycology but also forestry and allied areas where mushrooms are of economic importance. For example, over 60% of the data were retrieved from just eight countries in Asia, Europe, and North America: China (26.8%), Japan (7.4%), Germany (4.6%), Mexico (6.7%), Russia (4.2%), the UK (4.1%), India (3.5%), South Korea (3.2%), the USA (3.1%), and Italy (2.4%). This disproportionate representation does not necessarily suggest that these countries have a high diversity of edible mushrooms, but mainly that they have a strong culture surrounding their use, documentation, and research.

There were many more reports from North America and Europe, for example, compared with Africa, even though the consumption of wild mushrooms is common and widespread in large areas of the African continent (Härkönen, Niemelä, & Mwasumbi, 2003; Härkönen, Niemelä, Mbindo, Kotiranta, & Piearce, 2015; Rammeloo & Walleyn, 1993). China has seen an explosion of publications on mushrooms, with a strong emphasis on their useful properties to people (Wang et al., 2004; Wu et al., 2019). Mexico is another notable source of information on edible mushrooms (Garibay-Orijel et al., 2020). As a result of this bias, there are gaps in our data, for example, we present very little information on edible mushrooms consumed in Eastern Europe. However, we remain confident that the data captured on the edible properties of mushroom species are representative of all the major genera, though it is also clear that stronger evidence is needed to support decisions concerning the FES of many species.

5.3 | Food safety and regional variation in opinions on the edibility of wild mushrooms

There is ongoing debate and a degree of uncertainty regarding the edibility of a number of mushroom species, most of which are classified as E2 in our results. These are species that require a degree of preparation before being considered safe to eat and often the opinions regarding edibility differ regionally. For example, *Gyromitra esculenta*, known as the false morel, is commonly eaten in many countries, including Poland, Lithuania, Estonia, Finland, and Sweden, where it is sold in cans under the brand name Fammarps (https://www.natmat.se/produkt/murklor-190 g-fammarps). Elsewhere, for example, in Italy and Spain, field guides consistently advise that *G. esculenta* is poisonous and that it should be avoided at all costs. *Gyromitra* species contain toxic compounds such as Gyromitrin and poisoning incidents do occur (Leathem & Dorran, 2007; Michelot & Toth, 1991; White et al., 2019). Another example of a mushroom that is widely considered toxic in some regions and edible in others is *Chlorophyllum molybdites*. This species was responsible for more poisoning incidents in China in 2019 than any other species of mushroom (Li et al., 2020). Numerous other sources confirm that this mushroom is poisonous and should not be eaten (Bijeesh, Vrinda, & Pradeep, 2017; Lehmann & Khazan, 1992; Meijer, Amazonas, Rubio, & Curial, 2007), yet a wider literature search reveals that *C. molybdites* is consumed in nine states of Mexico (Villarreal & Perez-Moreno, 1989a). Rammeloo and Walleyn (1993), in their review of edible mushrooms in Africa, found case reports of *C. molybdites* being eaten in Madagascar, DR Congo, Republic of Congo, and Nigeria. Although there is no doubt that mushrooms such as *G. esculenta* and *C. molybdites* are toxic, these mushrooms can be, and are, eaten following thorough and careful cooking (Jarvinen, Kosonen, & Joutjarvi, 2004). Humans have evolved to eat cooked food, and few mushrooms are eaten raw; thus, when considering the edibility of mushrooms, greater emphasis should be given to the properties of cooked specimens.

Opinions on edibility vary with region; species that are prized in some cultures may not be sought after in others. The regional preferences for *Gyromitra esculaenta* have already been discussed above; other notable examples include *Schizophyllum commune*, *Phallus indusiatus* and *Tricholoma equestre*. *Schizophyllum commune* is a popular edible mushroom in China and India, yet few consider it as an edible in the West. Similarly, *P. indusiatus*, also known as the Long net stinkhorn, is sought after for soups in Asia, whereas yet many in the West consider it inedible. *Tricholoma equestre* remains a controversial choice as an edible mushroom, a study conducted by Bedry et al. (2001) reported that this species contains numerous toxins and is considered as potentially deadly to humans (Bedry et al., 2001); however, recent research has found no evidence that this mushroom is in fact toxic (Rzymski & Klimaszyk, 2018). As a result of this conflicting evidence, *T. equestre* is not eaten in many places; for example, it is listed as a poisonous mushroom in Spain, Italy, and France (Rzymski, Klimaszyk, & Benjamin, 2019). However, it remains sought after in parts of Asia and Europe. Although the debate on this species' edibility continues, our data support it as an edible species, though to be treated with a degree of caution.

6 | CONCLUSION AND FUTURE TRENDS

A rising awareness of the health benefits associated with eating mushrooms, and the recognition of mushrooms as a functional food, have resulted in an unprecedented increase in the consumption of mushrooms. Wild mushroom consumption, as well as other wild foods, is not without risks, and as such, public safety and awareness form an important part in managing the collection of wild mushrooms. Unfortunately, inaccurate taxonomy, lack of knowledge, or simply personal opinions have resulted in numerous conflicting reports on which mushrooms are edible and which are not safe to eat, creating a need for consensus of how to determine edibility and which species are in fact safe to eat. Our work proposes a standard method for addressing these issues. We recommend that all future reports should clearly indicate the source of evidence to support their assessments. An edible mushroom is one that has been safely consumed by a known person or population; however, some form of documentation is required to carry this information to a broader audience.

An edible mushroom is one that is safe and suitable to eat. Opinions differ on taste, texture, and smell, and it is important to separate subjective judgments on what is worthwhile to consume from an objective assessment of whether a mushroom can be consumed without adverse effects.

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AUTHOR CONTRIBUTIONS

Huili Li, Peter E. Mortimer, and Eric Boa designed and drafted the review; Nelson Menolli Jr, Lei Ye, Samantha C. Karunarathna, Jesus Perez-Moreno, Mohammad Mahmudur Rahman, Md Harunur Rashid, Pheng Phengsintham, Leela Rizal, Taiga Kasuya, Young Woon Lim, Arun Kumar Dutta, Abdul Nasir Khalid, Le Thanh Huyen, Marilen Parungao Balolong, Gautam Baruah, Sumedha Madawala, and Naritsada Thongklang contributed to the global data of wild edible mushroom. Paul M. Kirk contributed to the classification of wild edible mushroom. All authors contributed to the writing of the manuscript. The main revisions were carried out by Huili Li, Eric Boa, and Peter E. Mortimer; Nelson Menolli Jr, Kevin D. Hyde, Jianchu Xu, and Jun Sheng were involved in final review and completion of the paper.

ORCID

Huili Li https://orcid.org/0000-0002-6229-3780

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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