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REVIEW ARTICLE

Astraeus species (false earthstar): A comprehensive review of taxonomy, ecology, nutritional value, therapeutic potential and conservation

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Abstract

Astraeus species, notably *A. hygrometricus* and *A. odoratus*, are vital ectomycorrhizal fungi in tropical forests, forming symbiotic associations with host trees such as *Shorea robusta* and *Pinus kesiya*. These interactions enhance nutrient cycling, soil health, biodiversity and carbon sequestration, contributing to overall forest resilience. Culturally, *Astraeus* mushrooms serve as important seasonal food and medicinal resources for indigenous communities. Morphologically distinct from true earthstars (*Geastrum*), *Astraeus* species possess a hygroscopic exoperidium that opens into a star shape, a defining feature of the genus within Diplocystaceae (Boletales). Recent molecular phylogenetic studies have expanded the genus, resolved taxonomic ambiguities and revealed new species diversity across Asia. Ecologically and economically, *Astraeus* mushrooms function as significant non-timber forest products with promising nutraceutical and pharmaceutical potential due to their bioactive compounds. However, threats from deforestation, overharvesting, habitat loss and climate change endanger their populations. This review synthesises knowledge on taxonomy, ecology, ethnomycology, nutritional and pharmacological properties and conservation challenges, emphasizing the need for integrated sustainable management and further research to unlock their full ecological, nutritional and therapeutical potential.

Keywords: *Astraeus hygrometricus*; bioactive compounds; conservation; ectomycorrhizal fungi; ethnomycology; false earthstar; pharmacological properties

Introduction

Astraeus, commonly known as "False earthstars," is characterised by a hygroscopic exoperidium that splits radially upon exposure to moisture, producing a star-like morphology (1, 2). Although morphologically similar to *Geastrum*, *Astraeus* is phylogenetically distinct and differs structurally through the absence of a peristome and columella, as well as the presence of spiny basidiospores and branched capillitial hyphae (3, 4). Among the recognised species, *Astraeus hygrometricus* (Pers.) Morg. is the most extensively documented due to its wide distribution and ecological relevance. Its fruiting body initially appears as a puffball-like structure and later expands into a leathery star shape, with the exoperidium displaying hygroscopic movement that allows contraction during dry conditions and expansion during humid periods to facilitate spore release (5). The gleba gradually transitions from white to dusty brown as spores mature (3, 4).

Recent molecular studies have revealed greater species diversity within the genus, leading to the description of taxa such as *A. asiaticus*, *A. odoratus*, *A. koreanus*, *A. morganii*, *A. pteridis*, *A. smithii*, *A. sirindhorniae* and *A. telleriae* (6–8). These species exhibit variations in morphology, ecological preference and geographical distribution, highlighting the need for continued phylogenetic research. *Astraeus* species function predominantly as ectomycorrhizal fungi, contributing to nutrient uptake and soil improvement in nutrient-poor environments (9). In India, *A. hygrometricus* forms associations with *Shorea robusta*, *Tectona grandis*, *Syzygium cumini* and *Artocarpus hirsutus* (10, 11), while in northern Thailand it associates with *Pinus kesiya*, *P. merkusii* and *Shorea* spp. (12). Additional species, including *A. asiaticus*, *A. odoratus* and *A. koreanus* has been found associated with members of Dipterocarpaceae, Pinaceae, Myrtaceae and Fagaceae plants (5, 6, 13, 14). Unlike *Astraeus*, the saprotrophic genus *Geastrum* decomposes litter throughout the year and produces sulfurous terpenoids absent in *Astraeus* (15, 16). Fruiting in *Astraeus* commonly coincides with monsoonal rains (17, 18) and *A. hygrometricus* is traditionally consumed in Nepal, northern Thailand and South Bengal (19, 20).

Historical background and significance

The taxonomy of *Astraeus* has evolved significantly since its initial discovery. Originally described as *Geastrum hygrometricum* by Persoon in 1801, it was reclassified as *Astraeus hygrometricus* by Morgan in 1889, based on morphological features such as branched capillitial hyphae and larger spores (21). Although initially misidentified as *Geastrum* due to morphological similarities, molecular evidence has since confirmed its placement in the order Boletales (2, 3). The reclassification was also based on the absence of a hymenium and the presence of branched capillitia. Although with the advancement of technologies like ITS and LSU rDNA sequencing creation a separate genus *Astraeus* (20).

Astraeus species, especially *A. hygrometricus*, have been utilised in traditional medicine and local diets across regions like India, Thailand, Laos, China and Myanmar. Commonly known as "rugra," "puttu," "rotkeh," "hedphor" and "phutphut," these fungi are harvested during the monsoon season by tribal communities in Jharkhand, Chhattisgarh, West Bengal, Odisha, the Western Ghats and Southeast Asia (2, 4, 10, 12, 22–24). Serving as both dietary and medicinal products, they contribute significantly as non-timber forest products (NTFPs) in local economies (25, 26). Nutritionally, *Astraeus* species are rich in protein, fibre, essential minerals and vitamins, making them suitable for diabetic-friendly diets (27, 28).

Phytochemical studies have identified bioactive compounds, such as lanostane-type triterpenoids, flavonoids and polysaccharides, which exhibit antioxidant, immunomodulatory, hepatoprotective and antimicrobial activities (29–31). A novel glucan isolated from *A. hygrometricus* demonstrated significant immunostimulatory potential (32). Despite their nutritional and pharmacological benefits, *Astraeus* species remain underutilised due to lack of cultivation, with emerging research on species like *A. asiaticus* indicating potential for bioprospecting and sustainable applications in agroforestry and nutraceuticals (33, 34).

Scope and objective of review

This review synthesises historical, taxonomic, ecological, nutritional, ethnomycological and pharmacological knowledge on the genus *Astraeus*, with a focus on *A. hygrometricus*, *A. asiaticus* and *A. odoratus*. Emphasizing the diversity and usage of these species, we integrate classical taxonomy from Persoon (1801) and Morgan (1889) alongside contemporary ITS-based phylogenetic revisions that clarify species complexes and resolve long-standing misidentifications with *Geastrum* (2, 6, 8, 17, 31, 32). *Astraeus* species, being seasonally traded wild edibles and non-timber forest products, hold significant ecological, socio-economic value and ethnomycological importance in rural and tribal communities (35).

In Asia research on occurrence patterns and ecological niches (soil types, host associations, seasonality) with a focus on sal, dipterocarp and pine forest ecosystems were studied (36). Nutritional composition viz., protein, carbohydrates, fat, fibre, vitamins, minerals and micronutrient profiles of *Astraeus* sp. mushroom (11, 12, 28). The effect of different methods of consumption of the *Astraeus* mushrooms and the effect of steaming, boiling, grilling and pressure-cooking on alter phenolic compounds, antioxidants, bioavailability and functional properties would be assessed in future studies (19, 37). Similarly, assessment of metabolites viz., glucans, lanostane triterpenoids, phenolics, vitamins and their associated biological activities, including antioxidant, immunostimulatory, antidiabetic, antimicrobial, antileishmanial, hepatoprotective and cardioprotective effects would be carried out in future (38).

Documentation of vernacular knowledge, seasonal harvesting practices, market chains, medicinal uses (e.g., hemostatic spore use, burn salves) and the role of *Astraeus* species as non-timber forest products supporting local livelihoods (24, 26). Sustainable management requires conserving ectomycorrhizal habitats, community education and the integration of traditional ecological knowledge (39). These above-mentioned points highlighted the key research priorities, including the feasibility of cultivation, sustainable harvest management, standardisation of nutritional/biochemical assays, clinical validation of bioactivities and conservation of genetic diversity in changing forest ecosystems (2, 5, 8, 38).

Taxonomy and systematics

The morphological similarity between *Astraeus* (False earthstars) and *Geastrum* (true earthstars) has caused significant taxonomic confusion due to their star-like peridial dehiscence. However, phylogenetic, anatomical and ecological differences distinguish their evolutionary lineages and ecological roles (12, 40). *Astraeus* species are classified under Boletales, related to boletoid fungi, while *Geastrum* species belong to Geastrales within the gasteroid Basidiomycota lineage (1, 15). Molecular evidence confirms their evolutionary separation, with *Astraeus* deriving from boletoid ancestors, whereas *Geastrum* evolved independently toward gasteromycetization (15). Anatomically, *Astraeus* lacks a defined peristome, releasing spores through irregular ruptures, while *Geastrum* has a peristome for passive wind dispersal. The exoperidium in *Astraeus* is more complex, splitting into 5-13 rays, while *Geastrum* has simpler, more uniform rays. Differences in spore ornamentation, dispersal mechanisms and ecological preferences further distinguish the 2 genera (Table 1).

Classification and phylogenetic position within Boletales

Astraeus spp., or False earthstars, are gasteroid fungi in the Boletales order and Diplocystaceae family, forming ectomycorrhizal associations with trees in tropical and subtropical ecosystems (40). Initially classified under Geastraceae, molecular studies, including ITS and LSU rDNA sequencing, have established *Astraeus* as distinct from *Geastrum* (41, 22). Phylogenetically, it is closely related to *Scleroderma* and *Pisolithus* (16, 42).

Molecular analyses have identified 3 major species within *Astraeus* i.e., *Astraeus asiaticus*, *A. odoratus* and *A. hygrometricus*, with significant regional differentiation. The occurrence of *A. asiaticus* from all the tropical forest Northern and Eastern India, while *A. hygrometricus* and *A. odoratus* has been recorded in Korea as well as Jharkhand (43). Host relationships, such as those with *Shorea robusta* in India and *Dipterocarpus tuberculatus* in Thailand, influence species distribution (44). Genomic, transcriptomic and metabolomic approaches are recommended for resolving species complexes (6).

Table 1. Difference between *Astraeus* spp. and *Geastrum* spp.

Feature	*Astraeus* spp.	*Geastrum* spp.	Reference
Exoperidium (Outer Layer)	Hygroscopic; splits into 5-13 rays	Hygroscopic; splits into 4-10 rays	49
Endoperidium (Spore Sac)	Often irregular with apical pore	More regular, well-defined opening	49
Spore Dispersal Mechanism	Moisture-triggered “bellow” dispersal	Passive wind dispersal through peristome	47
Spore Ornamentation	Thick-walled, ridged spores	Smooth or finely ornamented spores	40
Gleba Maturity	Colour changes from white to black	Similar, but less ethnobotanically timed	17
Fruiting Location	Sandy/lateritic forest soils	Wide ecological range; less host-bound	15

Morphological identification of *Astraeus* spp.

The identification of *Astraeus* species is complicated by phenotypic plasticity and unreliable macromorphological traits. *Astraeus* fruiting bodies typically have globose or subglobose shapes with hygroscopic dehiscence, lacking distinct caps or stipes (11, 37). Traits such as habitat, host associations and morphological variations like ray number or spore colouration often fail to distinguish species within the *A. hygrometricus* complex (4, 43, 45). The exoperidium, comprising of suprapellis, mediopellis and subpellis, is essential for taxonomic identification and ecological function. It undergoes lobation during maturation to aid spore dispersal (46–48). Variations in exoperidial morphology and gleba characteristics assist in species differentiation. Microscopic techniques, such as SEM, show that *Astraeus* spores are coarsely ornamented, enhancing spore dispersal (40, 47).

Molecular identification characteristics of *Astraeus* spp.

Molecular tools, particularly ITS region sequencing, have advanced *Astraeus* taxonomy, revealing genetically distinct taxa like *A. odoratus* and *A. asiaticus*, previously misidentified under *A. hygrometricus* (48). Molecular analyses in India and Southeast Asia have highlighted host-specific genotypes, aiding taxonomic accuracy and herbarium curation (47). Despite these advancements, low interspecific divergence and a lack of comprehensive reference databases hinder ITS application (8). An integrative approach combining macromorphology, micromorphology and molecular methods is recommended for accurate identification. Molecular differentiation of *A. odoratus* and *A. hygrometricus* in Thailand, supported by ecological data, underscores the need for refined species boundaries (14, 46). Additionally, regional reliance on classical morphological taxonomy in areas like West Bengal, Jharkhand and Myanmar continues to cause inconsistencies in species identification (28, 44).

Life cycle and spore dispersal mechanism

The life cycle of *Astraeus* species, particularly in tropical and subtropical regions, is closely linked to environmental factors such as temperature, humidity and seasonal rainfall. These ectomycorrhizal fungi primarily fruit during the monsoon season (May to October) in South and Southeast Asia, with sporocarps emerging from underground or partially buried in lateritic soils, triggered by sufficient moisture (11, 33). The fruiting bodies exhibit hygroscopic dehiscence, where the exoperidium splits into star-like rays, facilitating optimal spore dispersal during wet conditions, hence the name "barometer earthstar" (17, 38). Temperature (26–35 °C) and humidity (78–94 %) are key factors for fruiting bodies formation (8, 53). Fruiting bodies transition from hypogeous to epigeous forms as they mature, with gleba colour changing from white (edible) to brown or black (inedible), guiding foragers in determining the correct collection time (48).

Geographical distribution

The genus *Astraeus* is widely distributed across tropical, subtropical and temperate regions, with the highest diversity and ecological specialisation observed in Southeast Asia (49–52) (Fig. 1, 2). In Southeast Asia, species such as *A. hygrometricus*, *A. asiaticus* and *A. odoratus* exhibit significant ecological diversity, particularly in northern Thailand, where they associate with ectomycorrhizal trees like *Dipterocarpus alatus* and *Shorea spp.* (17, 19, 53). These species fruit abundantly during the monsoon and are collected in local markets. Similar habitats are found in Myanmar, Laos, China and Japan (13, 14).

In India, *Astraeus* species are common in states like Jharkhand, Odisha, Chhattisgarh, Madhya Pradesh, West Bengal, Kerala, Himachal Pradesh and Uttarakhand (Fig. 3), where they associate with native trees like *Hopea parviflora* and *Artocarpus hirsutus* (2). In Europe, *A. hygrometricus* is found in southern France, Turkey and Eastern Europe, while in the Americas, *A. pteridis* is recorded in the southeastern USA (52). In Africa, *Astraeus* species are found in sub-Saharan regions and in Australia, they occur in eucalyptus forests (19). Molecular studies reveal a distinct Southeast Asian clade, supporting the hypothesis of Southeast Asia as the centre of evolutionary diversity for *Astraeus*, with species radiating to other continents through ancient land connections or long-distance dispersal (Fig. 4) (8).

Nutritional and phytochemical composition

Astraeus species viz., *Astraeus hygrometricus*, *Astraeus odoratus* and *Astraeus asiaticus*, are rich in essential nutrients and bioactive compounds that contribute to their therapeutic potential. Below is an overview of the nutritional composition of *Astraeus* spp., emphasising their roles as functional foods and medicinal agents (54).

Nutritional composition of *Astraeus* spp.

The nutritional profile of *Astraeus* species highlights their value as a food source, offering essential macronutrients and minerals. Fresh *Astraeus* fruiting bodies are low in fat, making them suitable for low-calorie diets, while their protein and carbohydrate content support muscle health, digestion and sustained energy. The high fibre content aids digestive health and helps regulate blood glucose levels (54, 55). The *Astraeus* mushrooms contain 65–75 % water content. Sensory cues, such as a firm white interior and almond-like aroma, indicate safe consumption, while discoloration or insect activity may suggest spoilage (17). On a dry weight basis, protein content ranges from 4.3 % to 35.11 %, carbohydrates from 30 % to 64.33 % and fibre from 7.3 % to 35.46 %. These nutritional values make *Astraeus* mushrooms particularly important in regions with limited food diversity, especially for populations with protein deficiencies (54, 56). The combination of protein, fibre and carbohydrates in these mushrooms supports a balanced diet while maintaining low fat levels, highlighting their potential as an essential food source (Table 2).

Bioactive Compounds

Astraeus species contain bioactive compounds such as phenolics, terpenoids, polysaccharides and carotenoids, offering antioxidant, anti-inflammatory and antimicrobial properties. The phenolic acids, like gallic acid and p-hydroxybenzoic acid, provide antioxidant and antimicrobial benefits (Table 3) (38). The total flavonoids of *Astraeus* (TFA) contain 6 chemical components including *β*-sitosterol, formononetin, calycosin, daucosterol, formononetin-7-*O*-*β*-D-glucopyranoside and calycosin-7-*O*-*β*-D-glucopyranoside which contributed to cardiovascular protection (11). Terpenoids, including astrakurkurone and astrakurkurol, exhibit anti-inflammatory effects (18). Polysaccharides, particularly β-glucans, enhance immune function and may possess anti-cancer properties (18, 33). Carotenoids like lycopene and β-carotene support eye health and act as antioxidants (11). Additionally, sterols in *Astraeus* species demonstrate cholesterol-lowering effects and promote metabolic health, including hormonal balance. These compounds highlight the medicinal potential of *Astraeus* for managing inflammation, chronic diseases

Table 2. Nutritional composition

Nutrient	g/100g fresh weight	g/ 100g dry weight	Reference
Protein	3.5-6.5 g	4.3-35.11 g	20, 25, 38
Carbohydrates	14-21 g	30-64.33 g	6, 18, 54
Fat	0.6-1.2 g	2.05-7.32 g	20, 56
Fiber	6.1-9.0 g	7.3-35.46 g	20, 25
Ash	1.5-2.3 g	-	17
Moisture	65-75 %	-	18, 54

Table 3. Different bioactive compound of *Astraeus* sp.

Compound	Content	Potential health benefits	Reference
Phenolic Acids	Gallic acid: 14.8 mg/100 g dry weight; p-hydroxybenzoic acid: 250 mg/100 g dry weight	Antioxidant, anti-inflammatory, antimicrobial	11, 38
Flavonoids	270 mg CE/100 g dry weight	Antioxidant, cardiovascular protective	11
Terpenoids	Astrakurkurone, astrakurkurol	Anti-inflammatory, antimicrobial	18
Polysaccharides	β-glucans, AQS-I (99.1 % glucose)	Immune modulation, anti-cancer	18, 33
Carotenoids	Lycopene, β-carotene	Antioxidant, eye health	11
Other Compounds	Trypsin inhibitors, Vitamin C, Ergosterol	Antimicrobial, digestive health, immune support	11, 33

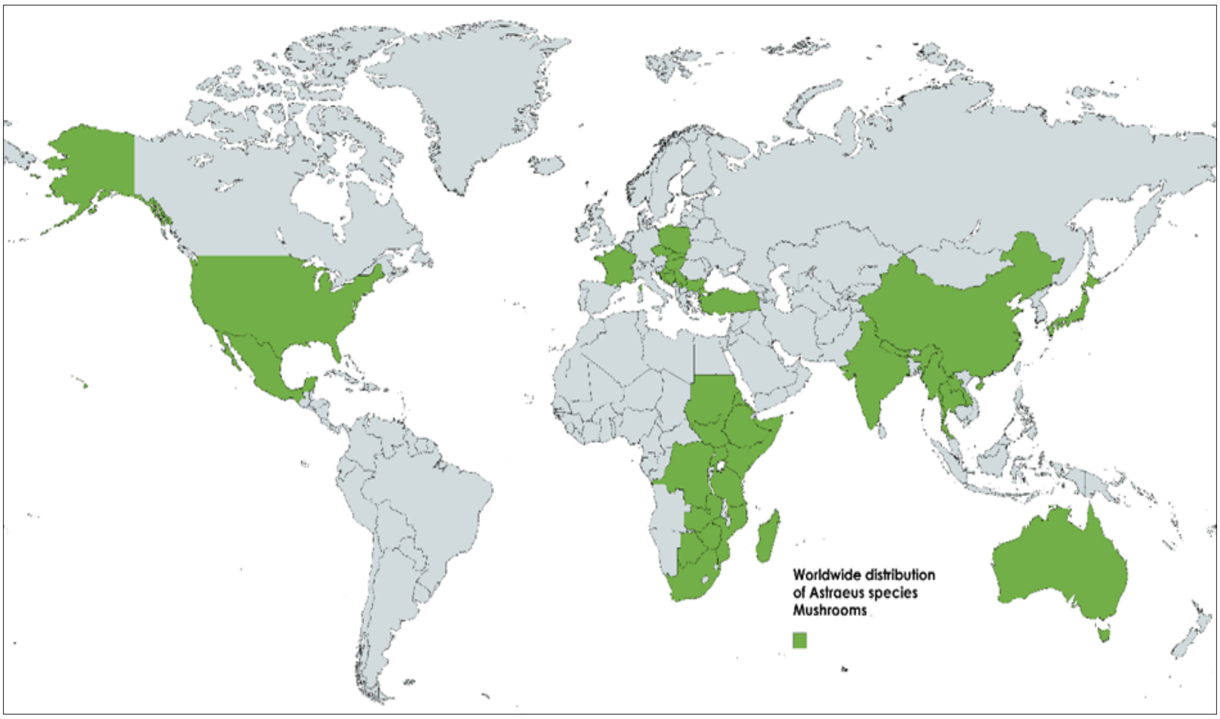


Fig. 1. Worldwide distribution of *Astraeus* species **.**

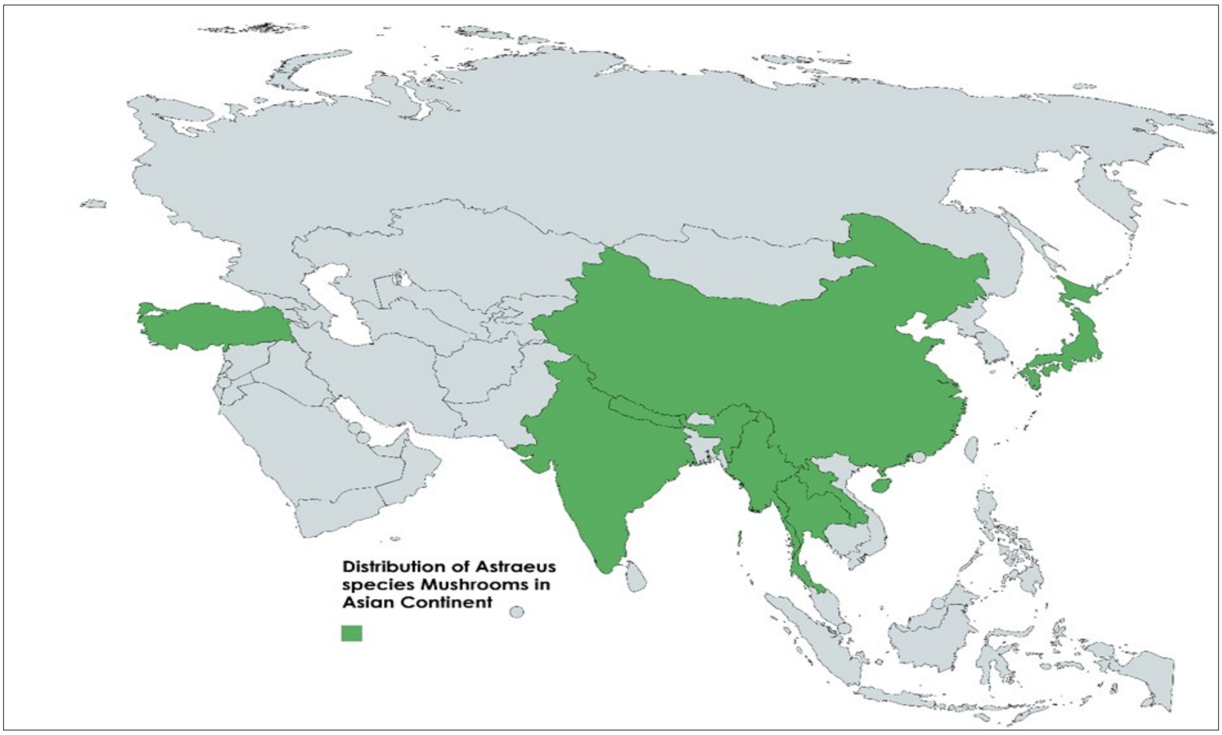
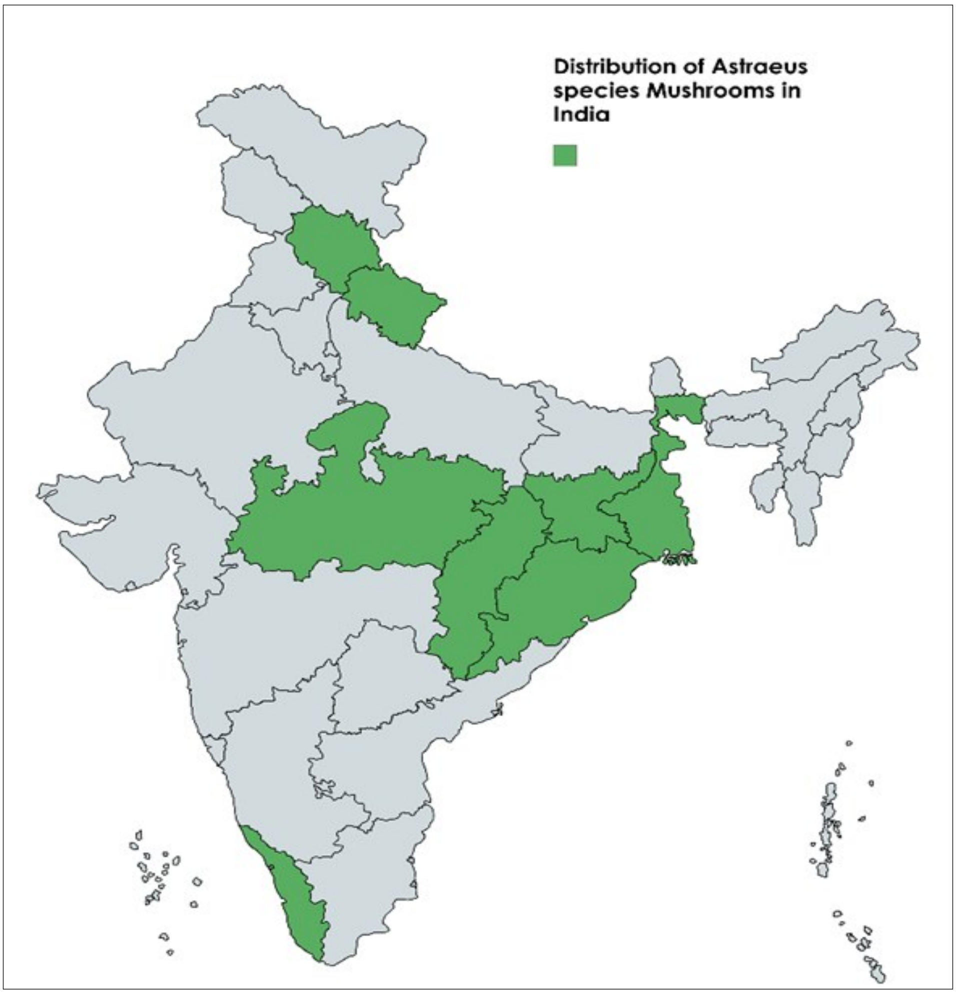


Fig. 2. Distribution of *Astraeus* species in Asian Continent.



Fig, 3. Distribution of *Astraeus* species in Asian continent.

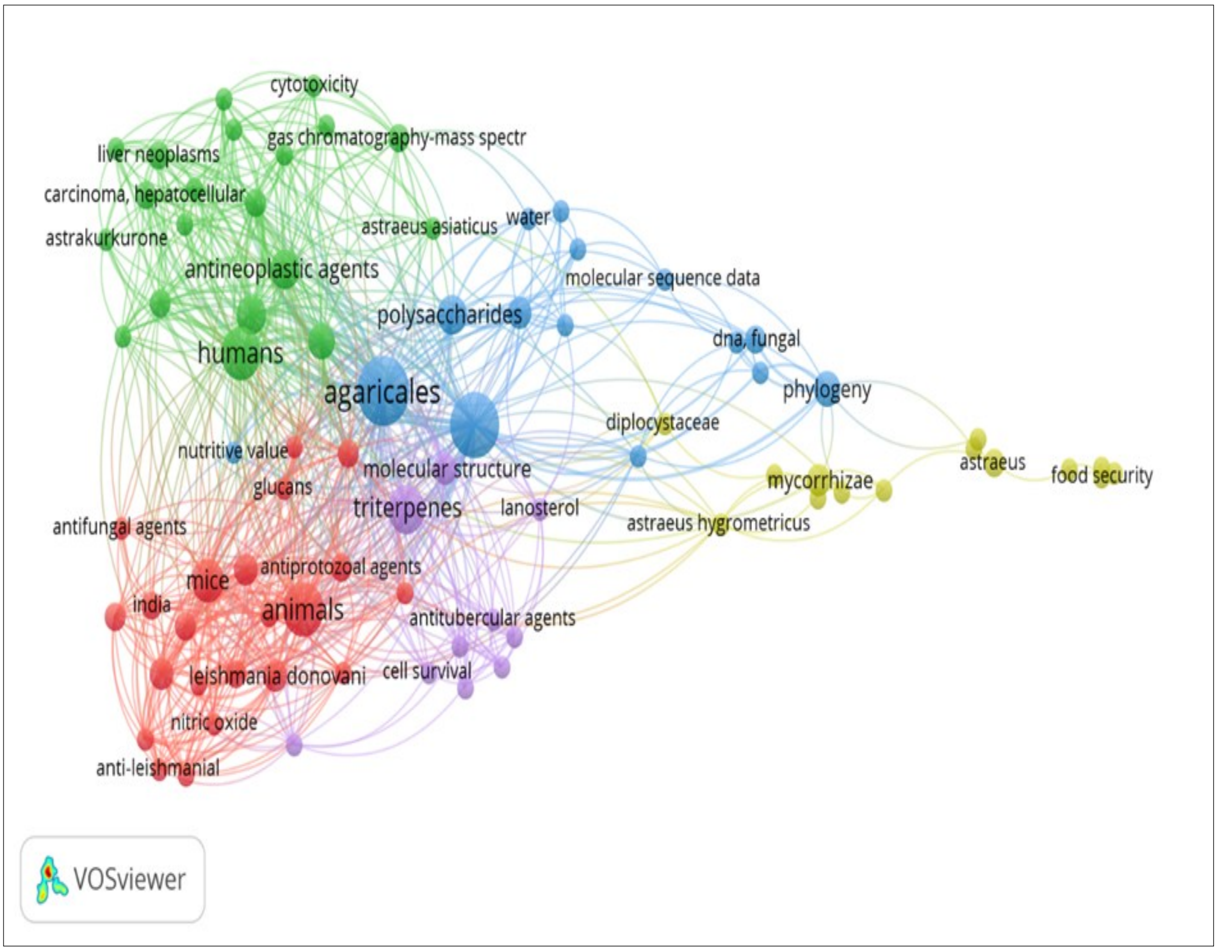


Fig. 4. An overview of the important terms associated with this review, generated by VOS viewer.

and supporting immune health (56, 57). The bioactive compounds further enhance their value as functional foods, supporting immune function, reducing inflammation and combating oxidative stress (29, 31).

Culinary value

Astraeus mushrooms, locally known as "kurkure," are highly valued in South and Southeast Asia for their umami-rich flavour, particularly during the monsoon season. Only immature, unopened fruiting bodies are considered edible and they are typically stir-fried, stewed, or used in curries (20, 24, 25, 58). The culinary preparation, while rooted in tradition, may reduce the antioxidant potential of mushrooms (59).

Culinary practices and cultural significance

In southern India, *Astraeus asiaticus* is a valued seasonal delicacy, especially in tribal regions, where immature fruiting bodies are fried or added to curries for their earthy flavour and firm texture (35, 60). In northern Thailand, *A. odoratus* is similarly esteemed, with only tender, immature mushrooms consumed for their unique taste and consistency (38). *Astraeus* species also play a role in indigenous medicine as dried fruiting bodies are applied to skin wounds and inflammations, while decoctions treat fevers and digestive ailments (18, 61). Economically, these mushrooms support seasonal income in remote areas, where they are sold fresh or sun-dried, reaching up to 410 Baht/kg in urban markets during the monsoon (17). Rising demand underscores the need for sustainable harvesting to avoid depletion of natural populations (4).

Effects of processing on bioactive compounds

Cooking affects the bioactive components of *Astraeus*, with some compounds like flavonoids and carotenoids reducing in concentration, while phenolic compounds become more extractable, potentially enhancing their antioxidant capacity (Table 4). Cooking may enhance the extractability of certain bioactive compounds, particularly phenolics, which could boost their health benefits (62– 64).

Preservation Techniques

Proper drying and storage are critical for maintaining the bioactive compounds in *Astraeus*. Different methods such as tray oven drying at controlled temperatures preserve antioxidant capacity and polysaccharide integrity (47). Drying methods like sun drying can reduce key bioactive components like β-glucans, while charcoal smoke curing may activate beneficial terpenoid compounds (65).

Storage techniques, including clay jars with neem leaves and vacuum-sealed bags, help maintain freshness and quality, with smoke-curing adding medicinal volatility (32). *Astraeus* is increasingly processed into value-added products such as gleba-based powders, capsules for antioxidant supplementation and topical ointments for anti-inflammatory use. These products are entering markets, particularly in the AYUSH-based nutraceutical sector (8).

Medicinal and therapeutical values

The genus *Astraeus*, particularly *A. hygrometricus* and *A. odoratus*, holds significant ethnomedicinal value in tribal regions of South and Southeast Asia. Traditionally, these species are used to treat fever, body aches, respiratory ailments and skin infections. Remedies include infusions with neem leaves for fevers, inhalation of smoke from burnt sporocarps for respiratory relief and topical application of fruiting body paste for wound healing (7, 35). In Odisha and Jharkhand, the gleba stage is considered therapeutically potent and ash mixed with mustard oil is used in treatments resembling African ethnomedicinal practices (51). Scientific investigations have begun to validate these traditional uses; for instance, ethanolic extracts of *Astraeus* have shown cytotoxicity against MCF-7 breast cancer cells, indicating chemopreventive potential (48). Additionally, extracts exhibit antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis* and *Candida albicans*, alongside preliminary antiviral properties that may involve disruption of viral replication (47).

Astraeus species, including *A. hygrometricus* and *A. odoratus*, are rich in bioactive compounds such as phenolics, terpenoids and polysaccharides, which contribute to their antioxidant, antimicrobial and therapeutic properties. These mushrooms hold significant potential in nutraceutical, pharmaceutical and functional food applications. Notably, their polysaccharides and lanostane-type terpenoids exhibit strong immunomodulatory and anti-inflammatory effects, making them promise for managing chronic inflammation and supporting immunotherapy (66).

Antioxidant properties

The antioxidant capacity of *Astraeus* species has been extensively studied and various assays, including DPPH, ABTS and FRAP, demonstrate significant free radical scavenging potential, primarily attributed to phenolic compounds, flavonoids and other metabolites (66). For example, *Astraeus odoratus* shows 279.5 mg AAE/100 g dry weight in DPPH scavenging activity (Table 5). This antioxidant activity helps mitigate oxidative stress by neutralising harmful reactive oxygen and nitrogen species (44).

Antimicrobial and antifungal properties

Astraeus species also demonstrate notable antimicrobial activity (Table 6) and various studies show efficacy against bacterial, fungal and parasitic pathogens, including *Candida albicans*, *Staphylococcus aureus* and *Mycobacterium tuberculosis* (7). The antimicrobial effects are mainly attributed to terpenoids and phenolic compounds, such as lanostane-type triterpenes and syringic acid. Volatile compounds like 1-octen-3-one in *Astraeus odoratus* contribute to its antifungal properties (66, 67).

The bioactive compounds in *Astraeus* contribute to both antioxidant and antimicrobial actions (Table 7). Polysaccharides like β-glucans have immunomodulatory effects, enhancing immune responses, while terpenoids and phenolic compounds offer anti-inflammatory and antimicrobial effects. Additionally, the osmoprotective role of compounds like trehalose and mannitol may stabilise cellular structures under stress (17, 68, 69).

Table 4. Effect of processing on bioactive compounds

Bioactive Compound	Pre-cooking levels	Post-cooking levels	Effect of cooking	Reference
Phenolic Compounds	Increased to 840 mg GAE/100 g dw	Increased	Increased extractability	62, 64, 65
Flavonoids	270 mg CE/100 g dw	Decreased	Decrease in content	62, 64, 65
Carotenoids	Lycopene, β-carotene	Decreased	Significant reduction	62, 64, 65

Table 5. Antioxidant content of *Astraeus* sp.

Antioxidant Assay	Result	Reference
DPPH Scavenging	279.5 mg AAE/100 g dry weight	44, 66
ABTS Scavenging	1,600.9 mg AAE/100 g dry weight	44, 66
FRAP	735.5 mg AAE/100 g dry weight	38, 44
DPPH Scavenging	63.87 % inhibition	11, 66
FRAP (other studies)	0.0293 ± 0.0012 nmol TE/g	18, 66

Table 6. Antimicrobial and antifungal properties of *Astraeus* sp.

Pathogen	Activity	Reference
Candida albicans	Inhibition of growth	18, 30
Mycobacterium tuberculosis	Inhibition of growth	18, 66
Leishmania donovani	Inhibition of growth	18, 67
Escherichia coli	Inhibition of growth	30
Staphylococcus aureus	Inhibition of growth	6, 66
Penicillium expansum	Inhibition of growth	7
Aspergillus tamari	Inhibition of growth	7

Table 7. Bioactive compound and their roles

Bioactive Compound	Functional property	Therapeutic effects	Reference
Phenolic Acids	Antioxidant, anti-inflammatory	Protects against oxidative stress, reduces inflammation	18, 38
Flavonoids	Antioxidant, anti-cancer	Protects against free radicals, may reduce cancer risk	11
Terpenoids	Antimicrobial, anti-inflammatory	Antifungal, antibacterial, anti-inflammatory	18, 67, 68
Polysaccharides (β-glucans)	Immunomodulatory, anticancer	Enhances immune response, may prevent cancer	18, 33

Immunomodulatory effects

Astraeus species, particularly *A. hygrometricus*, exhibit notable immunomodulatory activity attributed to their polysaccharides and lanostane-type terpenoids (Table 8). Polysaccharides such as AQS-I activate immune cells including splenocytes, T cells, B cells and macrophages with a dose-dependent response peaking at 10 ng/mL (70). These effects are mediated through NF-κB and MAPK signaling pathways, which regulate cytokine expression and immune cell activation (33). Additionally, lanostane-type terpenoids from *A. odoratus* and *A. asiaticus* enhance immune responses by promoting cytokine production and immune cell activity (71).

Anti-inflammatory effects

The anti-inflammatory effects of *Astraeus* species are attributed to their modulation of immune signalling pathways and suppression of pro-inflammatory mediators (Table 9). Polysaccharides such as AQS-I and AE2 have been reported to activate macrophages and influence cytokine production via NF-κB and MAPK pathways, which are central to inflammatory regulation (30, 33, 70, 72). Lanostane-type triterpenoids further contribute by downregulating inflammatory markers, notably COX-2 and IL-6, which are commonly associated with chronic inflammation (71). These compounds exert antioxidant effects that mitigate oxidative stress, enhancing their anti-inflammatory efficacy. Additionally, *A. odoratus* has been shown to activate the Nrf2/NQO1 signalling pathway, which plays a vital role in maintaining redox balance and cellular detoxification (73).

Anticancer and antileukemic properties

Astraeus species, particularly *A. hygrometricus*, have demonstrated selective cytotoxicity against leukemia cells, primarily through the intrinsic apoptotic pathway. Studies show that bioactive compounds like β-glucans and triterpenoids contribute to their anticancer properties, with promising implications for leukemia treatment (61, 74) (Table 10).

Antidiabetic and hyperlipidemic properties

Astraeus species have shown potential in managing blood glucose levels and lipid profiles, particularly *A. hygrometricus*. The polysaccharide fraction (AQS-I) has demonstrated immunomodulatory effects and comparable efficacy to cholesterol-lowering drugs like simvastatin, positioning *Astraeus* as a potential therapeutic for diabetes and hyperlipidemia (Table 11) (75, 76).

Bioprospecting for drug development

The diverse bioactive compounds in *Astraeus* species, including over 40 triterpenoids, phenolic compounds and polysaccharides, make them promising candidates for drug development (77, 78). These compounds have shown cytotoxic, anti-diabetic and immunomodulatory activities, which support the development of

Table 8. Immunomodulatory effects of *Astraeus* sp.

Bioactive Compound	Immunomodulatory effect	Mechanism	Reference
AQS-I (Polysaccharide)	Strong splenocyte activation	Dose-dependent activation, peaks at 522 % at 10 ng/mL	33
AE (Polysaccharide Fraction)	Enhanced splenocyte viability, macrophage phagocytosis	Activation of macrophages, cytokine production through NF-κB, MAPK pathways	70
Lanostane-type Terpenoids	Immunostimulatory pathways	Activation of immune cells, cytokine production	71
Glucan-rich Extracts	Enhanced immune response	Immunomodulation via cytokine production, macrophage activation	70

Table 9. Anti-Inflammatory effects of *Astraeus* sp.

Bioactive Compound	Anti-inflammatory effect	Signaling pathway	Reference
AQS-I (Polysaccharide)	Enhanced cytokine production	Activation of NF-κB and MAPK pathways	30, 33
AE2 (Polysaccharide Fraction)	Reduced inflammation, enhanced macrophage function	Inhibition of pro-inflammatory cytokine production	70, 72
Lanostane-type Terpenoids	Anti-inflammatory effects	Inhibition of COX-2 and reduction of IL-6	71

Table 10. Anticancer and antileukemic properties of *Astraeus* sp.

Species	Cytotoxicity	Mechanism of action	Reference
A. hygrometricus	Selective cytotoxicity against MOLT-4 cells	Activation of intrinsic apoptotic pathway	61, 74, 75
A. odoratus	Cytotoxic activity against cancer cell lines	Induction of apoptosis, inhibition of cell proliferation	18, 75
A. asiaticus	Potential anti-cancer activity	Cytotoxic effects via immune modulation	74

Table 11. Antidiabetic and hyperlipidemic properties of *Astraeus* sp.

Species	Effect on Blood Glucose	Effect on Lipid Profile	Potential Mechanism	Reference
A. hygrometricus	Significant reduction in blood glucose levels	Lowered LDL, raised HDL, reduced HbA1c	Polysaccharides (AQS-I), immunomodulation	61, 76
A. asiaticus	Blood glucose regulation in diabetic models	Improved lipid metabolism	Beta-glucans, terpenoids	18, 76

new therapeutic agents. Their high phenolic content also positions them as valuable resources for nutraceutical applications, particularly in antioxidant therapies (Table 12).

Ethnomycological and Cultural Relevance

Traditional uses by indigenous and rural communities

Astraeus species, particularly *A. hygrometricus*, *A. odoratus* and *A. asiaticus*, hold substantial ethnomycological, medicinal and economic significance across South and Southeast Asia (Table 13). Widely used in traditional medicine and local cuisines, they are especially valued in India, Thailand, Laos, Sri Lanka and China for treating burns, wounds and bleeding disorders (5, 17, 18, 79, 80). Among indigenous Indian communities such as the Baiga, Gond, Ho and Munda, these mushrooms are known by vernacular names like *puttu*, *rugra*, *sehula*, *rotkeh* and *patangallo* (7, 8, 24).

Cultural and seasonal practices surrounding *Astraeus* collection are deeply rooted in local traditions. In India, Thailand and Laos, *A. hygrometricus* is highly prized for its medicinal and culinary uses (4). Fruiting typically occurs during monsoon rains, prompting seasonal harvesting by women and children in rural areas (11, 17). Immature fruiting bodies with firm, white gleba are favoured for consumption, while overripe specimens are avoided due to their bitterness and possible toxicity (4). Traditional cooking methods include boiling, roasting or frying, often with coconut milk, tamarind, or spices.

The mushrooms serve multiple roles in traditional medicine. Dried powders and decoctions are used for skin wounds, fevers, digestive complaints and general malaise (18, 61). Although scientific validation is ongoing, these persistent folk practices suggest a pharmacological foundation that warrants further investigation. *Astraeus* species are considered nutraceuticals, valued for their antioxidant, anti-inflammatory, hepatoprotective and cardioprotective potential. They are believed to support immunity, enhance digestion and prevent chronic illness, particularly among rural populations in India, Laos and Thailand (4, 17).

From an ecological and conservation perspective, *Astraeus* species are more vulnerable to habitat degradation due to their ectomycorrhizal associations and narrow habitat preferences, in contrast to the widely distributed saprobic *Geastrum* species (8). Conservation strategies should include monitoring of host trees and soil conditions, along with accurate species identification through molecular tools such as DNA sequencing (41). Sustainable harvesting, based on indigenous ecological knowledge such as assessing gleba colour and aroma demonstrates a community-based model of resource stewardship (29, 48).

Beliefs, taboos and rituals associated

While formal taboos regarding the harvesting of *Astraeus* mushrooms are not widely documented, indigenous knowledge systems guide selective harvesting practices based on sensory and ecological cues. Foragers traditionally assess edibility through visible indicators such as gleba colour, odor and the presence of insect activity (5). Mature or blackened specimens are avoided due to their bitterness and potential toxicity (7, 25, 40), reflecting a deep understanding on the developmental stages of the fungus and associated risks.

Market Trends and Commercialisation

Astraeus species, particularly *A. hygrometricus* and *A. odoratus*, are increasingly commercialised for their nutritional and medicinal value. In India, fresh mushrooms retail at ₹400– ₹800/kg, while dried forms reach ₹1200 –₹2200/kg (6). Exported extracts sell for $18– $30 per 100 g, with demand rising across ASEAN markets (25). The supply chain includes forest gatherers, village aggregators and exporters, supported by NGOs and SHG-led initiatives promoting ethical trade and value-added products (25, 57). However, challenges persist, such as lack of botanical standards, limited shelf-life data and unclear customs codes (61). GI tagging is proposed to enhance traceability and cultural branding. Young entrepreneurs are developing tools like foraging apps and eco-tourism ventures (32). Yet, unregulated commercialisation risks ecological damage, prompting calls for “mycorrhizal stewardship,” integrating conservation, enterprise and local governance (8).

Table 12. Bioprospecting for drug potential of *Astraeus* sp.

Bioactive Compound	Pharmacological Activity	Therapeutic Potential	Reference
Triterpenoids (Lanostane-type)	Cytotoxic, anti-inflammatory, immunomodulatory	Cancer therapy, immune enhancement, anti-inflammatory	14, 71
Polysaccharides (β-glucans)	Immunomodulatory, anticancer, antidiabetic	Diabetes management, cancer therapy, immunoadjuvants	18, 33
Phenolic Compounds	Antioxidant, anti-inflammatory	Antioxidant therapies, anti-inflammatory agents	6, 48
Volatile Compounds (1-octen-3-ol)	Antimicrobial, flavour enhancement	Natural product-based therapeutics, food flavoring	14, 79

Table 13. Traditional uses by indigenous and rural communities

Region/Culture	Medicinal Use	Conditions Treated	Reference
India	Folk medicine	Diabetes, cancer, liver ailments, fatigue, digestive disorders	6, 34
Laos, Thailand	Herbal remedies, poultices	Immune-boosting, wound healing, digestive health, skin infections	17, 70
China	Folk medicine	Hepatoprotection, anti-inflammatory, wound healing, anti-diabetic	18, 80
India and China	Seasonal dietary supplements	Immuno-enhancement, anti-inflammatory, fatigue relief	24, 80

Conservation strategies for *Astraeus* species mushrooms

Overharvesting and habitat degradation

The sustainability of *Astraeus* species especially *A. hygrometricus*, *A. odoratus* and *A. asiaticus* is threatened by rising demand, habitat degradation and unregulated harvesting. Overextraction, particularly in laterite and *Shorea robusta* forests, disrupts ectomycorrhizal associations essential for fungal fruiting (6, 11, 41). Immature sporocarp collection and weak enforcement in degraded forests further exacerbate resource depletion (24, 25). Logging of host trees like *Shorea robusta*, *Dipterocarpus tuberculatus* and *Terminalia bellirica* undermines fungal viability, especially for *A. odoratus* and *A. asiaticus* (5, 29).

Climate sensitivity and mycorrhizal specificity

Astraeus species are obligate ectomycorrhizal fungi with narrow ecological niches, forming symbiotic relationships with tree genera such as *Pinus*, *Shorea* and *Dipterocarpus* (11, 33). Their fruiting is synchronised with monsoonal rainfall, typically from June to October and reliant on lateritic soils, making them vulnerable to climatic shifts and habitat disturbance (17, 61).

Climate-induced changes in precipitation and temperature pose threats to their reproduction and host-specific distribution (6, 41). The associations such as *A. hygrometricus* with *Dipterocarpus tuberculatus* and *A. asiaticus* with *Shorea robusta* and *Madhuca indica* further heighten vulnerability, requiring climate-resilient conservation strategies (29, 48).

Need for sustainable harvesting

To ensure the long-term sustainability of *Astraeus* populations, integrating indigenous ecological knowledge with scientific conservation strategies is essential. Community-based efforts that incorporate traditional understanding of seasonal fruiting, habitat needs and harvesting practices can improve conservation outcomes (6, 70). Educating forest-dependent communities on sustainable collection, while protecting ectomycorrhizal host trees, is critical for maintaining viable habitats (11).

Agroforestry-based cultivation under host species, such as *Shorea* and *Dipterocarpus*, is recommended for balancing conservation with rural livelihoods (17). Although many tribal harvesting practices are inherently sustainable, further community engagement and systematic documentation of ethnobotanical knowledge are needed (4, 61). Conservation frameworks should prioritise localised planning, host tree regeneration, fungal habitat protection and biodiversity monitoring (5, 33, 48). Market incentives and regulatory guidelines can further align conservation with rural development goals (25, 29, 40).

Cultivation aspect exploration

Attempts to cultivate *Astraeus* species face significant challenges due to their obligate ectomycorrhizal nature, requiring a symbiotic relationship with specific tree hosts like *Dipterocarpus tuberculatus* and *Shorea robusta* (29, 48). Unlike saprotrophic fungi, *Astraeus* requires specific soil conditions, moisture regimes and compatible host roots, making large-scale artificial cultivation unfeasible (11). While some laboratory success has been reported, substantial gaps remain in propagation techniques and ecological understanding (6, 41). The continued reliance on wild-harvested specimens highlights the lack of standardised cultivation protocols and the dependency on natural forest ecosystems for commercial supply (7, 24).

Future Directions and Research Gaps

Need for genome sequencing and metabolic profiling

Taxonomic ambiguity in *Astraeus* persists due to reliance on morphological traits, though molecular tools like ITS sequencing have improved species resolution (50). However, whole-genome data remain unavailable, limiting insights into cryptic species and evolutionary convergence (49). Metabolomic studies are also incomplete; while triterpenoid and phenolic biosynthesis have been partially explored (14), full pathway elucidation is lacking (20). Future research should prioritise genome sequencing, metabolomics, cultivation systems, immunological assays and bioactive delivery innovations (Table 14) (81).

Conservation biology and sustainable livelihoods

Astraeus species, especially *A. hygrometricus*, rely on ectomycorrhizal associations with forest trees, making intact ecosystems essential for survival and sustainable harvesting (11, 17). These fungi support tribal food sovereignty, provide seasonal income and promote biocultural conservation, with cultivation potential aiding biodiversity and rural livelihoods (29, 40).

Sustainable management involves conserving ectomycorrhizal habitats, educating local communities and integrating traditional ecological knowledge (20, 25). *Astraeus* contributes to forest resilience, though cultivation remains limited due to complex root associations and ecological dependencies (6, 41). Progress in synthetic cultivation, mycorrhizal inoculants and agroforestry may support domestication (47).

Future strategies require interdisciplinary collaboration across taxonomy, ecology, pharmacology and ethnomycology to conserve *Astraeus* while unlocking therapeutic and economic potential (7, 14). Genome sequencing, biochemical profiling and socio-ecological integration are crucial for food security, conservation and health innovation (25).

Environmental triggers and climate modelling

Environmental cues for fruiting especially monsoonal moisture, temperature and soil conditions remain poorly understood (11). AI -based phenology modeling and GIS-based mycorrhizal mapping could enhance sporocarp emergence forecasts and inform forest zoning and conservation strategies (5, 29).

Pharmacological and nutritional research

While studies indicate that *Astraeus* extracts possess antioxidant, antimicrobial and anticancer properties, there is a clear need for *in vivo* validation and detailed mechanistic investigations (7, 38). The future research should focus on cytokine modulation, apoptosis pathways and human bioavailability assays. Nutritional profiling under varying thermal conditions is needed to standardise health claims and assess processing effects on phytochemical stability (25).

Table 14. Future direction and research gaps

Research Focus	Expected outcome	Reference
Molecular Taxonomy	Bioactive compound identification	6, 41
Metabolomics	Elucidation of biosynthetic pathways	24, 48
Ecological Monitoring	Sustainable habitat management	5, 29
Cultivation Studies	Reduction in wild harvesting pressure	14, 25
Collaborative Research	Improved conservation and food security	7, 20

Ethnomycology and cultural knowledge integration

Ethnomycological data are under-documented. Local narratives and spiritual beliefs surrounding *Astraeus* can inform ecological research and bioprospecting efforts. A "story-driven science" approach is recommended, integrating traditional knowledge with empirical methods to preserve indigenous taxonomy and ecological insights (17, 25).

Sustainable harvesting

The increasing demand for *Astraeus* species has raised concerns about overharvesting and habitat degradation (Table 15). To mitigate these risks, sustainable practices such as rotational foraging, size-based collection and seasonal harvesting restrictions during spore dispersal are recommended (4). Community-based conservation initiatives are essential to preserving these species and supporting the livelihoods of local communities (25).

Conservation efforts and policy recommendations

Ex situ conservation efforts, such as tissue culture and cryopreservation, will be utilized in preserving *Astraeus* species, although successful *in vitro* fruiting remains a challenge (47). Policy initiatives such as including *Astraeus* in biodiversity registers and promoting organic mushroom cooperatives can help empower local communities and protect these valuable species (4). Future research should focus on creating fungal conservation corridors, using citizen science platforms and integrating fungal conservation into climate resilience models (25). The identification and mitigation of all the threats to the *Astraeus* population would be achieved through fundamental policies preparations on deforestation, overharvesting, climate change, soil degradation and urbanisation (Table 16).

Conclusion

Astraeus species play an essential ecological role as ectomycorrhizal partners that enhance nutrient cycling, soil stability and forest resilience across tropical ecosystems. Their ethnomycological and nutritional value is complemented by substantial medicinal potential, with diverse bioactive metabolites demonstrating antioxidant, immunomodulatory, anti-inflammatory and therapeutic properties. Despite of such importance application and uses, *Astraeus* remains understudied, particularly in genomic, transcriptomic and metabolomic contexts that are crucial for resolving species complexes and their utilisation in pharmacological applications and their domestication. The Increasing habitat disturbance, climate change and unsustainable harvesting further threaten natural populations, underscoring the urgent need for conservation frameworks that integrate ecological protection with community-based management. Advancing genomic research, research on domestication, sustainable utilisation and habitat preservation will be vital for safeguarding *Astraeus* species diversity and maximising its ecological and therapeutic benefits.

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Authors' contributions

VK conceptualized the review, conducted the literature search and analysed relevant studies. VK, AC wrote sections of the manuscript, revised and finalised by the author. The author approved the final version of the manuscript for submission.

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Table 15. Sustainable harvesting practices for *Astraeus* spp.

Practice	Description	Impact	Reference
Rotational Foraging	Alternating harvest zones to allow regeneration	Prevents depletion of local populations	4
Size-Based Collection	Harvesting mature fruiting bodies	Protects immature spores and ensures future growth	25
Seasonal Restrictions	Limiting harvesting during spore dispersal	Ensures natural reproduction and population stability	4

Table 16. Major threats to *Astraeus* populations

Threat	Description	Impact
Deforestation	Logging, mining and infrastructure projects	Loss of host trees, disrupted mycorrhizal networks
Overharvesting	Unregulated collection during peak fruiting	Decline in mycelium and fruiting body density
Climate Change	Altered rainfall, temperature patterns	Irregular fruiting, reduced symbiosis efficiency
Soil Degradation	Agrochemical runoff, soil compaction	Poor conditions for fungal growth
Urbanisation	Encroachment on forest edges	Habitat fragmentation, biodiversity loss

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