Ecological Characteristics of *Floccularia luteovirens*

Subjects: Mycology

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Floccularia luteovirens, a rare wild edible and medicinal fungus, is endemic to the Tibetan plateau. However, attempts to artificially domesticate this species have not been successful, resulting in extremely limited utilization of this valuable resource. The geographical distribution of *F. luteovirens,* along with its ecological and biological characteristics are presented. It explores population relations, symbiotic relationships, soil microbial community relations, fruiting body occurrence conditions, nutritional metabolism, and reproductive patterns. The cultivation techniques, as well as the edible and medicinal value of this mushroom, are also reviewed. Through an overall analysis of the physiological characteristics and current research status of *F. luteovirens*, its development prospects were discussesed.

Keywords: *Floccularia luteovirens* ; ecological characteristics

1. Introduction

Edible fungi are a diverse group of large fungi with unique physiological characteristics and a wide range of forms. They are known for their delicious taste, rich nutrition, and diverse bioactive ingredients, making them a popular choice for healthy eating [1]. Among edible fungi, mycorrhizal fungi are a special type that form a symbiotic relationship with plants, relying on host plants to provide the necessary nutrients for their growth [2]. Research has shown that many mycorrhizal edible fungi have higher protein and trace element contents compared to saprophytic edible fungi [3][4][5]. *Floccularia luteovirens* (*Alb. & Schwein.*) *Pouzar* is a rare wild edible fungus found in the Qinghai–Tibet Plateau of China. It forms mycorrhizal symbiosis with *Kokanica humilis* and plays an important role in the alpine meadow or grassland ecosystem [6][7]. This mushroom is a local delicacy and has significant economic value. Additionally, it has been used as a traditional Tibetan medicine with notable effects in hypoglycemic, antioxidant, anti-tumor, and immune regulation [8]. Therefore, *F. luteovirens* holds great potential as a resource for functional food or medicine. However, as a local resource, the research on *F. luteovirens* is still very limited. Many aspects of this species remain unknown, such as the specific mechanism of fruiting body production, artificial culture conditions for mycelium, and the form of action of pharmacologically active ingredients. The inability to achieve commercial cultivation further restricts its processing and utilization. Additionally, environmental changes and overpicking contribute to the increasing scarcity of this resource.

2. Taxonomy of *F. luteovirens*

F. luteovirens is a member of the Basidiomycota phylum, belonging to the Agaricomycetes class, the Agaricales order, and the Agaricaceae family within the Floccularia genus [9]. This edible mushroom is commonly referred to as a golden mushroom or grassland yellow mushroom by local residents [10]. The taxonomic status of *F. luteovirens* has been controversial and misunderstood for a long time. It was previously thought to belong to the genus Armillaria, under the Physalacriaceae family, and was therefore referred to as *Armillaria luteovirens* in various studies [11], and is still used today. Gan et al. [12] assembled and annotated the genome of *F. luteovirens*. Through phylogenetic tree analysis, they determined that *F. luteovirens* belongs to the Agaricaceae family and that its species differentiation occurred approximately 170 million years ago. Liu et al. [13] conducted rDNA-ITS sequence determination on 36 *F. luteovirens* strains isolated from field collection in Qinghai Province, and then, combined with comparative genomic data, further confirmed that *F. luteovirens* should be classified under the genus Floccularia rather than the genus Armilaria. The NJ phylogenetic tree showed that the *F. luteovirens* C10 strain was closer to the species of Tricholomelaceae in a phylogenetic relationship and clustered with *Floccularia albolanaripes* with a bootstrap value of 99%. As a result, the NCBI database has also replaced the species *Armillaria luteovirens* with *Floccularia luteovirens* (NCBI: txid493452) in 2019.

3. Ecological Characteristics of *F. luteovirens*

3.1. Geographical Distribution and Population Relationship of *F. luteovirens*

F. luteovirens is primarily found on the Qinghai–Tibet Plateau in China. Its geographical distribution range in China is approximately latitude 28°93′–37°69′ N and longitude 90°4′–102°1′ E [7]. It is most commonly found in the grasslands or alpine meadows of Qinghai and Tibet, with smaller populations in the western part of Sichuan and the southern part of Gansu [14]. This species has also been reported in the Altai Republic of Russia and Mexico [15][16]. According to reports [6][17][18], the altitude distribution range in Qinghai province is around 3000 to 4300 m, with the majority of sightings occurring in meadows between 3200 and 3800 m above sea level. The main areas of production include Haibei, Huangnan, Hainan, Guoluo, Yushu, and other regions. In Tibet, the altitude distribution ranges from about 3200 to 4600 m. The highest point in the Qomolangma region can reach up to 5000 m above sea level. Significant production areas for *F. luteovirens* include Lhasa, Dazi, Langkazi, Pali, Bangda, Dingri, and others. In Shiqu County, Sichuan Province, *F. luteovirens* mainly grows in the grasslands along the Yalong River at an altitude of 4000–4300 m. The geographical structure of *F. luteovirens* exhibits significant differences. A comprehensive analysis of 91 samples from 10 geographical groups in Qinghai, Tibet, and Sichuan provinces revealed that the population genotype comprises two branches. Researchers aslo found that population genetic variation primarily originates from within the population, with substantial genetic differentiation observed between populations [19]. Moreover, the genotype diversity (h) of *F. luteovirens* ranged from 0.385 to 0.876, indicating a moderate level of genetic diversity [20].

3.2. Symbiotic Relationship of *F. luteovirens*

F. luteovirens is a symbiotic mycorrhizal fungus that forms a partnership with the Kobresia plants. The hyphae of this fungus are distributed in the soil at a depth of 5–30 cm. During the fruiting bodiy harvest season, white mycelia can be observed on the roots of *Kobresia humilis* [6]. Although many scholars agree that *F. luteovirens* is an ectomycorrhizal fungus [20][21], there is a lack of anatomical or modern biological identification, and its mycorrhizal types need to be further clarified. Ectomycorrhiza symbiosis is a widespread association between the roots of woody plants and soil fungi in forest ecosystems [22]. Examples of mycorrhizal edible fungi include matsutake, boletus edulis, and truffle, which form symbiotic relationships with pine or oak trees [23]. However, the fruiting body of *F. luteovirens* occurs in alpine meadows, where the dominant vegetation consists of *K. humilis* and alpine weeds [24]. In Guo et al.'s study, they used a metagenomic method to determine the diversity of endophytic fungi in *K. humilis*. They found that *F. luteovirens* is one of the dominant endophytic fungi in *K. humilis* [25]. The habitat of *F. luteovirens* often forms a ribbon-like fairy ring, with a circle width of approximately 50 cm and a diameter of about 6 m [24]. According to Shantz and Piemeisel's classification of fairy rings, the fairy ring formed by *F. luteovirens* falls under type II [26]. This means that the existence of the fairy rings stimulates the growth of plants, and there is only a green grass ring without a dry grass ring. Fairy rings are a well-known ecological landscape found in grasslands, and a similar phenomenon can be observed in the fairy ring formed by *Leucocalocybe mongolica* in the Mongolian Plateau [27]. Additionally, the plants within the *F. luteovirens* ring exhibit higher biomass, plant height, and plant density compared to those outside the ring [6][28]. The formation of a fairy ring is a distinctive occurrence resulting from the growth of fungal mycelium in the soil. Several studies have demonstrated [29][30][31] that Fairy Ring fungi can produce plant growth regulatory substances to stimulate plant growth, such as 2-azahypoxanthine (AHX) and imidazole-4-carboxamide (ICA), and regulate the activity of various enzymes in the soil, thereby improving soil characteristics and providing favorable conditions for plant growth. The plants on the fairy rings displayed a noticeable increase in greenness, and the abundance index and species diversity index of the plant communities on the rings were significantly higher. The promotion of plant growth by *F. luteovirens* is closely linked to the mycorrhizal system. On the one hand, plants are able to contribute to the decomposition and activation of mineral elements in the soil through a vast network of hyphae, particularly enhancing the absorption of organophosphorus and other nutrient elements. On the other hand, plants can also serve as a source of carbon for fungi in the form of sugar or fatty acids [32]. *F. luteovirens* can change minerals into usable organic forms by releasing organic acids. This makes roots absorb more minerals and improves the stress resistance of symbiotic plants. [33]. Physiological and metabolomic analysis has shown [34] that *F. luteovirens* can influence the accumulation of soil metabolites, regulate plant carbon/nitrogen metabolism, and enhance the growth of above-ground tissues in alpine meadow plants. Meanwhile, it may also reduce root growth to adjust the root-shoot ratio, consequently increasing nutrient accumulation in plants. In addition, the mycelium of *F. luteovirens* also produces volatile organic compounds (VOCs) that regulate the distribution of root auxin, thereby controlling the root development of plants. This, in turn, affects the growth, metabolism, and environmental adaptability of plants [35]. Andrea Polle et al. have also discovered that ECM fungi produce volatiles, particularly terpenoid derivatives, which can influence the development of host plants and their lateral roots [36]. This finding is similar to the role of *F. luteovirens* in regulating plant growth. The fairy ring effect, caused by the growth and metabolism of mycelia, has significant impacts on the plant-soil ecosystem in the habitat. It can alter the inter-specific competitive relationship of grassland communities and influence the composition and direction of plant community succession [37]. However, the growth of *F. luteovirens* has a minimal effect on the uniformity and succession of plant communities [24]. In conclusion, as an endemic species, *F. luteovirens* plays a positive role in regulating plant growth and maintaining ecosystem stability in the alpine meadows of the Qinghai–Tibet Plateau.

3.3. Soil and Soil Microbial Communities

The soil of the *F. luteovirens* habitat is dark, with a pH range of 6.8–7.2 and a humus layer measuring 10–20 cm. Below the humus of the soil is the parent material, containing gravel and grass roots [6][18]. The decomposition of fungal mycelia can enhance the mineralization of soil organic matter and release nutrients, thereby enriching the soil and significantly increasing the availability of nutrients. In the fairy ring area, the soil within the ring exhibits higher levels of nutrients and enzyme activities compared to both the inside and outside areas of the ring [38]. In the 0–10 cm soil layer, the soil water content, available phosphorus, nitrate nitrogen, and ammonia nitrogen content in the fairy ring formed by *F. luteovirens* were significantly higher than outside the circle [24][33]. Floccularia is the absolute dominant genus among soil microorganisms in *F. luteovirens* nest soil, with a relative abundance of 85.76%. The FunGuild function predicted that the soil fungi in the habitat of *F. luteovirens* were mainly symbiotic, followed by saprophytic [39]. This finding aligns with the mycorrhizal symbiotic nature of *F. luteovirens*. The presence of *F. luteovirens* in the soil has a regulatory effect on the microbial community. In the area where mycelia grow, the diversity of bacteria increases while the diversity of fungi decreases [33][40]. The possible reason is that the interspecific cooperation in mycorrhizal symbiosis between *F. luteovirens* and *K. humilis* enhances the competitive ability of *F. luteovirens* and inhibits the vitality of other fungal species in a limited ecological niche. Ectomycorrhizal (ECM) fungi play a crucial role in the rhizosphere community by interacting with various microorganisms. One of the main interactions involves the competition between different ECM fungi as they strive to occupy the root space of the host in order to obtain additional carbon sources [41]. A study on the fairy ring formed by *F. luteovirens* revealed interesting findings. The number of operational taxonomic units (OTUs) in the three regions was as follows: 300 in the IN region, 1107 in the ON region, and 14 in the OUT region. No other ECM fungi were detected in any of the three regions, with only a small amount of arbuscular mycorrhizal fungi being detected. These results suggest potential competition between *F. luteovirens* and other ECM species [33]. The presence of *F. luteovirens* in the soil has indirect effects on the composition and metabolism of soil microorganisms. This, in turn, leads to changes in the distribution and composition of metabolites in the soil. It is important to note that microorganisms in the soil have an impact on the development of mycelia, mycorrhizal synthesis, and fruiting bodies in *F. luteovirens* [40]. Soil bacteria and fungi play different roles in affecting soil nutrients, soil enzyme activity, and microbial activity [42]. At present, numerous comparative studies have already been conducted on soil microbial species in the vicinity of the *F. luteovirens* fairy ring. Further research could focus on the effects of enzymes secreted by fungi, particularly those originating from *F. luteovirens*, on the rhizosphere soil environment of plants.

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