Research Article **Open Acces**

Assessment of Bioluminescent Fungi and Their Ecological Relationship in Mount Halimun Salak National Park, West Java Province

Danik Septianingrum[1,2,3], Samuel Anju Lumbantoruan[1,3], Nurah Anggraeni[1,3], Faiza Utami[1,3], Alya Raisa Karina[1,3], Muhammad Hisyam Fadhil[1,2,4], Jason Raditya Santosa[1,4], Sindi Pramanik Maharani[1,4], Ali Dzulfigar[1,5], Zidan Craig Abdurrohim[1,3], Abd. Malik A. Madinu[1,6], Aulia Ulfa[1,2,3], Yasmin Nuha Nabilla[1,3], Salsabila Nur'aini[1,2,5], Isma Nurul Khofifah[1,3], Nandhita Setyaningrum[1,7], Ari Wardana Hendriatna[1,8], Rahmat Asy'Ari[1,2], Yudi Setiawan[9,10], Ardi Sumanto[11]

[1] *IPB Sustainable Science Research Student Association (IPB SSRS Association), IPB University, Bogor Regency 16680, Indonesia*
[2] *SSRS Indonesia Biodiversity Hub, SSRS Institute Indonesia, Bogor Regency, West Java Province, Indonesia*
[3] *Undergraduate of Department of Biology, Faculty of Mathematics and Natural Sciences, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[4] *Undergraduate of Department of Agronomy and Horticulture, Faculty of Agriculture, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[5] *Undergraduate of Department of Silviculture, Faculty of Forestry and Environment, IPB University, Bogor Regency 16680, Indonesia*
[6] *Undergraduate of Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[7] *Undergraduate of Department of Forest Product, Faculty of Forestry and Environment, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[8] *Undergraduate of Department of Forest Management, Faculty of Forestry and Environment, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[9] *Undergraduate of Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry and Environment, IPB University, IPB Dramaga Campus, Bogor Regency 16680, Indonesia*
[10] *Center for Environmental Science, Lembaga Penelitian dan Pemberdayaan Masyarakat IPB, IPB University, Bogor Regency 16680, Indonesia*
[11] *Agency of Gunung Halimun Salak National Park, Ministry of Forestry of Indonesia, Sukabumi Regency, West Java, Indonesia*

* Correspondence: septianingrumdanik@gmail.com

Abstract: Bioluminescent fungi are fungi that possess unique structures and are capable of emitting light (bioluminescence). Gunung Halimun Salak National Park (GHSNP) is one of the habitats of bioluminescent fungi, with its ecosystem consisting of tropical rainforest and high rainfall. The research conducted aimed to determine the bioecology of the habitat, including air temperature, air humidity, substrate pH, shading vegetation, macromorphology, and population density of bioluminescent fungi. Data collection was carried out during night and day using the purposive random sampling method in two observation plots at the Cikaniki Research Station, GHSNP. The ecological data collected included air temperature and humidity, which were gathered as time series data, and canopy cover, analyzed using hemispherical photography. Results showed that bioluminescent fungi inhabit moist environments with substrates consisting of dead wood or litter layers that have an acidic pH. Based on time series collection, bioluminescent fungi experience daily air temperatures ranging from 20–24 °C and air humidity levels between 84–98%. Two species of bioluminescent fungi were found in both observation plots, namely *Mycena* sp., characterized by white fruiting bodies measuring 1.2 cm, and Species X, which remains unidentified. Population density in Plot 2 was higher compared to Plot 1, reaching 9 individuals per plot. The type of vegetation in the habitat of bioluminescent fungi in Plot 2 was also more diverse and accompanied by understory plants such as begonias, palms, and ferns, resulting in a more humid habitat and a greater distribution pattern in Plot 2 compared to Plot 1. Differences in population density between plots of bioluminescent fungi in each plot indicate that habitat and environmental factors influence the distribution pattern and growth of bioluminescent fungi.

Keyword: Bioclimate, Bioluminescent Fungi, Mycena

SSRS Publishing

Septianingrum D, Lumbantoruan SA, Anggraeni N, Utami F, Karina AR, Fadhil MH, Santosa JR, Maharani SP, Dzulfigar A, Abdurrohim ZC, Madinu AMA, Ulfa A, Nabilla YN, Nur'aini S, Khofifah IN, Setyaningrum N, Hendriatna AW, Asy'Ari R, Setiawan Y, Sumanto A. 2025. Assessment of Bioluminescent Fungi and Their Ecological Relationship in Gunung Halimun Salak National Park, West Java Province. *SSRS Journal A: Agro-Environmental Research*. 3: 42 – 56

INTRODUCTION

Bioluminescent fungi are fungi that are able to emit light due to their bioluminescent capability. The light emitted by the fungi serves to attract insects, including beetles, flies, wasps, and ants, which aid in the dispersal of fungal spores in the surrounding area, considering that wind currents beneath the forest canopy are not strong (Rush and Jenuarista 2019). Several fungi believed to possess bioluminescent capability originate from the families Mycenaceae, Omphalotaceae, Pleurotaceae, and Physalacriaceae, with Mycenaceae being the most abundant, comprising 69 taxa (Arya *et al.* 2021). The tropical rainforest ecosystem in Indonesia serves as a suitable habitat for bioluminescent fungi due to its relatively stable temperature and sunlight throughout the year. Most bioluminescent fungi commonly found in Indonesia are *Mycena chlorophos*. This species is widely distributed in forest ecosystems with diverse substrates, ranging from branches, dead and decayed wood, to leaf litter on the forest floor (Noverita *et al.* 2018). Gunung Halimun Salak National Park (GHSNP), specifically in the Cikaniki resort, is one of the forest ecosystems where bioluminescent fungi are frequently found. The presence of these fungi has also become an icon of the resort (Hasibuan and Jenuarista 2019). This is due to the forest ecosystem conditions in GHSNP, which is categorized into a tropical rainforest with high rainfall.

Bioluminescent fungi possess a unique structure unlike most other fungi, particularly in their ability to emit light, a trait not found in all organisms. Therefore, bioluminescent fungi have become an interesting subject of study and are currently being widely researched by other scientists. This is due to the limited amount of information available regarding the facts about bioluminescent fungi. For example, research conducted by Qurniawati and Ratnawulan (2021) focused on the characterization and optimization of growth conditions for bioluminescent mushrooms. In addition, a study by Sharma and Gupta (2024) examined the causes and mechanisms of bioluminescence in bioluminescent fungi.

However, among the studies that have been conducted, there has yet to be research that examines in depth the correlation between ecological habitat conditions and ecosystem characteristics on the growth of bioluminescent fungi. Therefore, this study was conducted to determine how bioecological factors including canopy density, substrate pH, time, air temperature, and air humidity affect population density as well as the growth and development of bioluminescent fungi. By understanding the factors that influence the distribution and abundance of

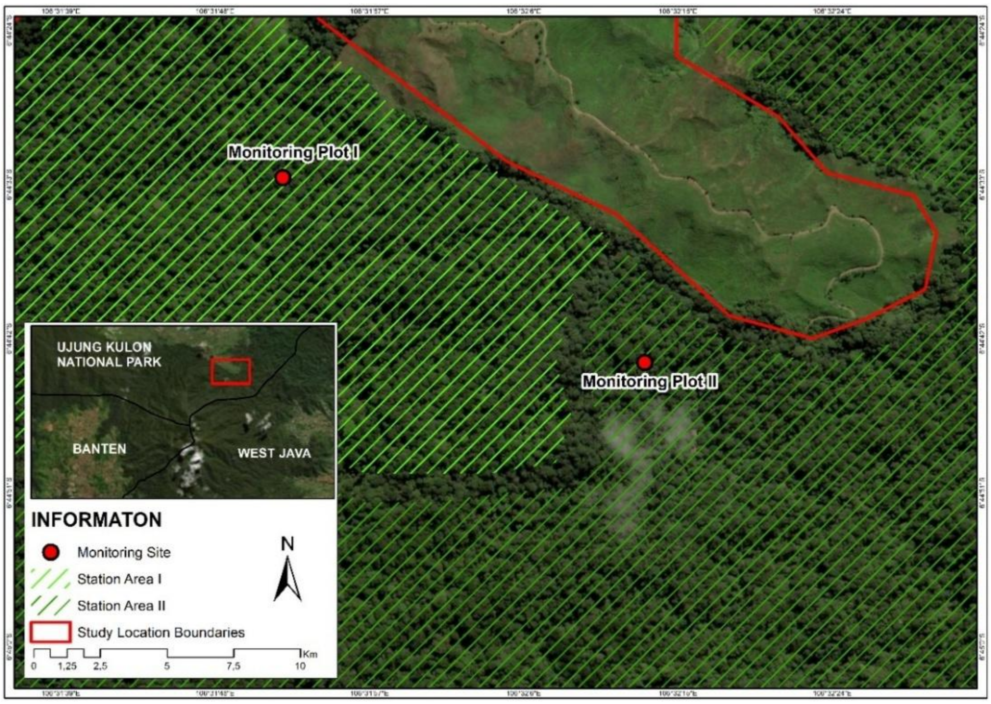


Figure 1. Research location area in Cikaniki Research Station of GHSNP

bioluminescent fungi, it is expected that this can serve as a basis for developing more effective conservation strategies to preserve the existence of bioluminescent fungi and maintain ecosystem balance.

METHODOLOGY

Study Area

The survey was conducted at the Cikaniki Research Station, Gunung Halimun Salak National Park (GHSNP), Nanggung District, Bogor Regency. Cikaniki Station is located in the eastern part of GHSNP at an elevation of 900 meters above sea level, covering an area of 2,782.59 hectare**a**, and at the Citalahab camping ground situated at an elevation of 1,070 meters above sea level, with an area of approximately 3 hectares.

Data Collection

The tools and materials used during the survey included a hygrometer, pH meter, camera, ruler, tally sheet, fish-eye camera, and writing instruments. Sampling was conducted on May 26, 2024, from 19:00 to 00:00 WIB using the purposive random sampling method, namely direct observation in areas where bioluminescent mushrooms were growing, using 1×1 m plots. Data collection was carried out in two observation plots: Plot 1 and Plot 2. The data collected included the number of mushroom individuals per plot (for density analysis), morphological identification of understory vegetation in Plot 2, bioclimate characteristics (pH, air temperature, air humidity, and hemispherical imagery), number and type of understory plants, shading vegetation (seedlings, poles, saplings, and trees), canopy openness, and LAI (Leaf Area Index).

Data Analysis

The collected data were processed using several analytical techniques, including analysis of macromorphological characteristics of the mushrooms, analysis and identification of understory vegetation, analysis of bioclimate characteristics, analysis of the relationship between mushrooms and vegetation, analysis of the relationship between mushrooms and bioclimate, and analysis of mushrooms and their habitat. The analysis of macromorphological characteristics of the mushrooms, referring to Putra (2020), included substrate type, stipe height, color of the fruiting body (before and after bioluminescence), and species name, assisted by identification applications such as iNaturalist or Google Lens, as well as relevant literature. Identification of understory vegetation was conducted solely based on species names, assisted by identification applications (iNaturalist or Google Lens) and relevant references.

To understand the relationship between the presence of bioluminescent mushroom species and one of its environmental factors which is pH, a categorical comparison analysis was performed and visualized in the form of a bar plot. The relationship with other bioclimate variables, namely air temperature and humidity, was assessed using time series data. Time series data collection involves gathering data with consideration of temporal factors, where data are collected at specific time intervals such as annually, quarterly, monthly, weekly, daily, or hourly (Diningestu and Mahmudah 2024). In this study, time series analysis

Table 1. Distribution pattern of bioluminescent mushrooms in night observation plot 1 (1 m × 1 m)

Plot No.	No. Of Individual Per Plot	Path Length (m)	Substrate	Species	Density Between Plots (Number of Individuals/m²)
1	3	6,57	Dead tree branches/twigs	*Mycena* sp.	3
2	2	6,57	Dead tree branches/twigs	*Mycena* sp.	2
3	2	6,57	Dead tree branches/twigs	*Mycena* sp.	2
4	1	6,57	Dead tree branches/twigs	*Mycena* sp.	1
5	1	6,57	Dead tree branches/twigs	*Mycena* sp.	1

Table 2. Shading vegetation in observation plot 1 (daytime observation)

No	Vegetation type	Species	Diameter (cm)	Amount
1	Tree	Rasamala (*Altingia excelsa*)	23	1
2	Tree	Type A (not identified yet)	-	1
3	Tree	Type B (not identified yet)	-	1
4	Tree	Type C (not identified yet)	-	1
5	Stake	Saninten (*Castanopsis argentea*)	6	1
6	Stake	Ipis kulit (*Decaspermum fruticosum*)	4	1

Table 3. Distribution pattern of bioluminescent fungi in night observation plot 2 (1m x 1m plot)

Plot No.	No. Of Individual Per Plot	Path Length (m)	Substrate	Species	Density Between Plots (Number of Individuals/m²)
1	3	6,57	Dead tree branches/twigs	*Mycena* sp.	3
2	2	6,57	Dead tree branches/twigs	*Mycena* sp.	2
3	2	6,57	Dead tree branches/twigs	*Mycena* sp.	2
4	1	6,57	Dead tree branches/twigs	*Mycena* sp.	1
5	1	6,57	Dead tree branches/twigs	*Mycena* sp.	1

of air temperature and humidity was conducted at one-hour intervals. The shading vegetation of the bioluminescent mushroom habitat was analyzed using hemispherical photography to determine LAI (Leaf Area Index) and canopy openness values, which indicate the degree of canopy cover.

RESULTS AND DISCUSSION

Distribution of Bioluminescent Fungi

Bioluminescent fungi found in plots 1 and 2 exhibited different distribution patterns (Tables 1 and 3). In observation plot 1, there were 5 replicates with 1 to 3 individuals per replicate, and the path length was 6.57 meters. The bioluminescent fungus observed in plot 1 (Table 1) was *Mycena* sp., growing on dead wood twigs. The environmental conditions in plot 1 during nighttime observation included an air temperature of 21.6 °C and humidity of 98%. Trees and saplings present in plot 1 included rasamala (*Altingia excelsa*), Species A, Species B, Species C, saninten (*Castanopsis argentea*), and ipis kulit (*Decaspermum fruticosum*) (Table 2).

The bioluminescent fungi found in plot 2 (Table 3) consisted of 6 replicates, with 1 to 9 individuals observed and a path length of 23.35 meters. The fungi identified in plot 2 included *Mycena* sp. and Species 1, growing on litter and woody twig substrates. The environmental conditions in plot 2 differed from those in plot 1, with an air temperature of 21.7 °C and humidity of 84.6%. The understory or seedlings growing near the fungi consisted of three types: begonias, ferns, and palms (Table 4), while the trees and saplings present in plot 2 included saninten (*Castanopsis argentea*), burunungkul (*Blumeodendron elateriospermum*), pasang reueuy (*Lithocarpus* sp.), rasamala (*Altingia excelsa*), and ki sauheun (*Orophea hexandra*) (Table 5).

Table 4. Distribution of understory/seedling vegetation around observation plot 2 (daytime observation)

Plot No.	Species/Family/Local Name
1	Begonias
	Palms
	Species 1
	Species 2
	Species 3
	Species 4
	Species 5
2	Ferns
	Palms
	Species 1
	Species 2
	Species 3
3	Begonias
	Palms
	Ferns

Table 5. Shading vegetation in observation plot 2 (daytime observation)

No.	Vegetation type	Species	Diameter (cm)	Amount
1	Tree	Saninten (*Castanopsis argentea*)	63	1
2	Tree	Burununggul (*Blumeodendron elateriospermum*)	53,3	1
3	Tree	Pasang Reueuy (*Lithocarpus* sp.)	53,3	1
4	Tree	Rasamala (*Altingia excelsa*)	38	1
5	Pole	Ki Sauheun (*Orophea hexandra*)	16,7	1

Mycena sp. fungi in both observation plots demonstrated their ability to thrive by degrading decayed wood and leaf litter substrates. *Mycena* sp. possesses the capability to break down lignin, cellulose, and hemicellulose through the production of extracellular enzymes, making it an important decomposer of organic matter in forest ecosystems. This role contributes significantly to nutrient cycling and serves as a vital source of nutrients for surrounding vegetation (Putra *et al.* 2017).

The inter-plot density results of bioluminescent fungi in plots 1 and 2 showed differing outcomes, with the highest density found in plot 2 (Table 3). The variation in fungal density between plots

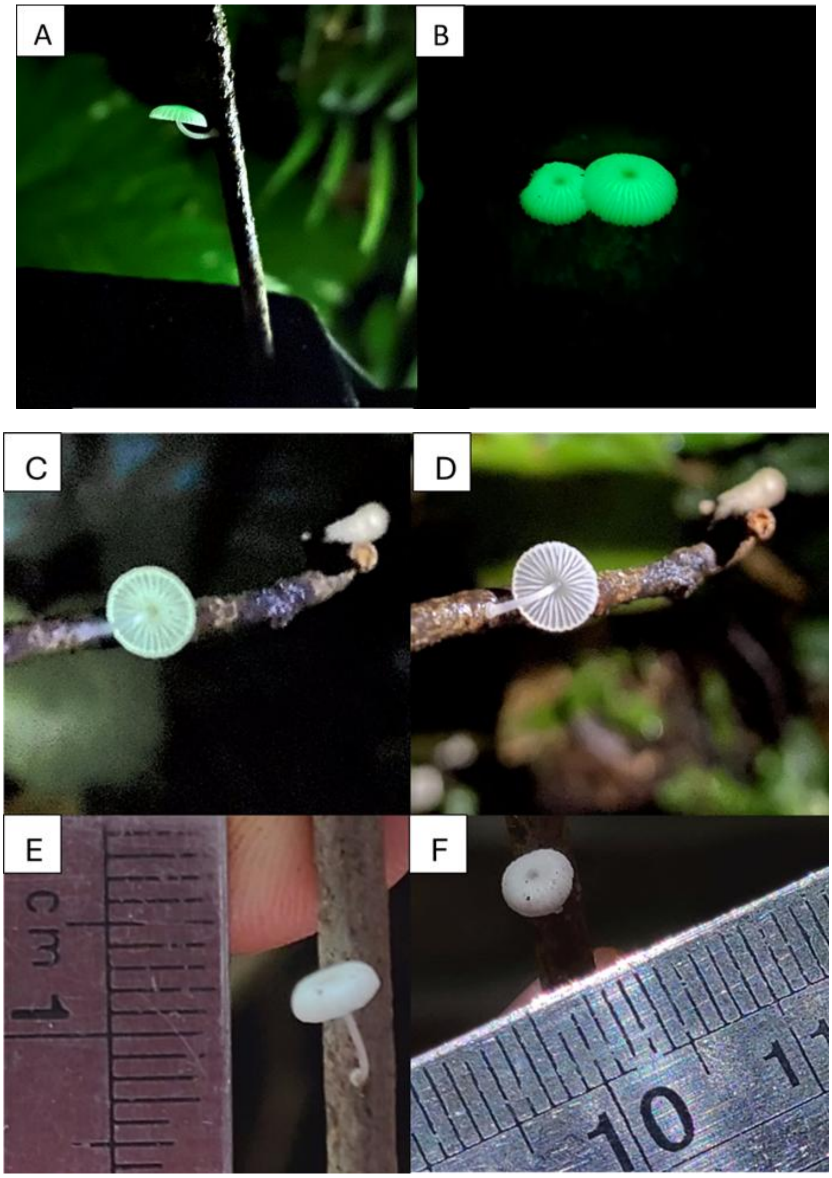


Figure 2. Bioluminescent fungus Species 1 (*Mycena* sp.): A) bioluminescent fungus on woody twig substrate, B) pileus of the fungus glowing at night, C) hymenophore glowing at night, D) hymenophore during the day, E) height of the bioluminescent fungus, F) pileus diameter of the bioluminescent fungus.

indicates the influence of habitat and environmental factors, leading to differences in substrate abundance for bioluminescent fungi (Wati *et al.* 2019).

Mycena sp. exhibited the highest density in plot 2, growing on leaf litter and twigs, due to its role as a decomposer that helps maintain ecosystem balance, particularly in nutrient availability for plants (Putra *et al.* 2017). The attachment of *Mycena* sp. to substrates in plot 2 was more sheltered because of the denser vegetation compared to plot 1, resulting in lower light intensity. This condition led to higher humidity in *Mycena* sp.'s habitat in plot 2, contributing to its greater distribution compared to *Mycena* sp. in plot 1.

Macromorphology of Bioluminescent Fungi and Phases of Bioluminescent Fungi

The bioluminescent fungi found in both observation plots consisted of two different species: one identified as *Mycena* sp., and the other remained unidentified (Species X). However, based on macroscopic characteristics, this unidentified species shares many similarities with *Marasmiellus* sp. To date,

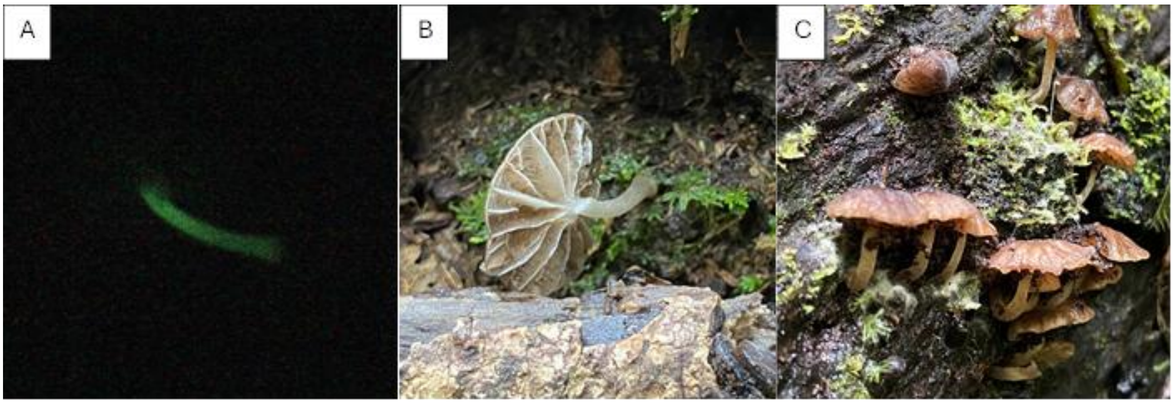


Figure 3. Bioluminescent fungus Species 2 (Species X): A) condition of the bioluminescent fungus at night, B) condition of the bioluminescent fungus during the day, C) colony of bioluminescent fungus Species 2.

Figure 4. Habitat of bioluminescent fungi findings: a) observation plot 1, b) observation plot 2

however, there are no known records of bioluminescent capability within the *Marasmiellus* group.

Mycena sp. was found growing solitarily, with macroscopic characteristics including a white fruiting body. It has a parabolic-shaped cap, a lamella-type hymenophore with moderately spaced gills, and a fruiting body size of 1,2 cm (Figure 2). In contrast, Species 2 was found growing in colonies, with macroscopic features including an orange-brown fruiting body, a lamella-type hymenophore with distantly spaced gills (Figure 3).

Mycena sp. fungi found in plots 1 and 2 exhibited bioluminescence across nearly all stages of fruiting body development, from the early umbrella-inverted cap phase to the fully expanded cap. In general, weak bioluminescence in small fungi indicates that the mushroom has not yet fully opened. The bioluminescence process in the *Mycena* group, particularly in *Mycena chlorophos*, is typically divided into four phases.

The four phases of the bioluminescence process are: Phase A (when the mushroom cap is drooping downward and not yet glowing), Phase B (when the cap begins to open and emits a faint glow), Phase C (when the cap is fully open to wavy and glows at maximum intensity), and Phase D (when the cap bends upward like an inverted umbrella and no longer

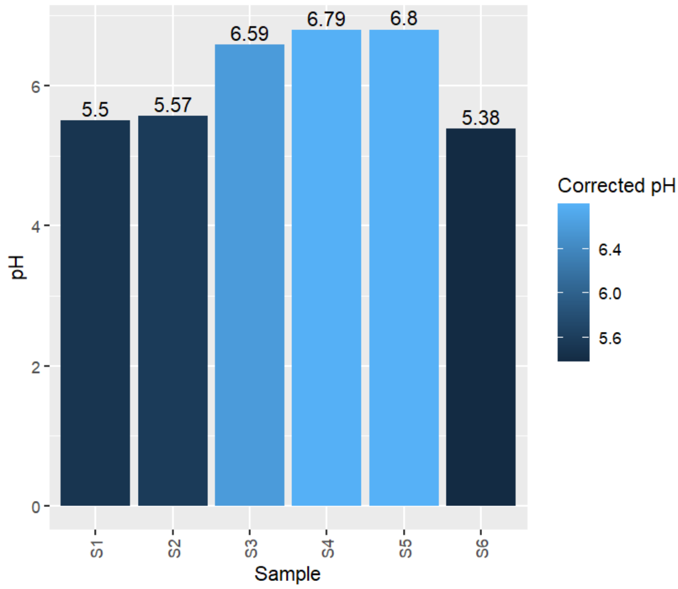


Figure 5. Corrected pH value of soil samples from the habitat

glows) (Teranishi, 2016). Meanwhile, Species X displays bioluminescence only on its stipe (Figure 3).

In contrast to *Mycena* species, the bioluminescence in Species 2 occurs only on the stipe (Figure 3). Fungal bioluminescence is produced through a chemical reaction that results in a steady emission of light at maximum intensity, typically within the 520–530 nm wavelength range, and is associated with secondary metabolites produced by the fungus (Lee, 2022). Four main components are involved in this chemical reaction: luciferin, luciferase, energy, and oxygen.

Luciferin is catalyzed by the enzyme luciferase, a biological catalyst that accelerates and regulates the rate of chemical reactions in cells in the presence of oxygen. Bioluminescent fungi possess a unique metabolic pathway involving several additional enzymes besides luciferase (Sharma & Gupta, 2024). These fungi emit green light (around 530 nm) from their fruiting bodies or mycelia when luciferin is broken down. Oliveira *et al.* (2012) discovered that a single biochemical process is shared among all four monophyletic lineages of bioluminescent fungi due to the presence of a common luciferin compound and luciferase enzyme. Ecologically, bioluminescence in fungi functions to attract insects for spore dispersal, which is especially advantageous for fungi growing on the forest floor where wind flow is limited (Oliveira *et al.* 2015).

Habitat of Bioluminescent Fungi

Forest Characteristics

Gunung Halimun Salak National Park (GHSNP) is the largest tropical rainforest area in West Java and harbors high biodiversity, including serving as a habitat for bioluminescent fungi (Hani *et al.* 2014). The habitat of bioluminescent fungi in the area around Cikaniki Station, GHSNP, is highly diverse and includes two observation plots with distinct characteristics. The forest characteristics in the vicinity of Cikaniki Station, GHSNP, are shown in Figure 4.

The habitat condition of bioluminescent fungi in plot 1 (Figure 4A) was characterized by the presence of fungi on dead wood twigs located in a forest area beside a footpath. In plot 2 (Figure 4B), bioluminescent fungi were found in a forest area with abundant fallen leaves and humid conditions, specifically within the fourth litter layer, consisting of a mix of twigs, surrounding small branches, and decaying wood. According to Noverita *et al.* (2018), fungi can inhabit a variety of environments as long as those habitats provide a source of nutrients and suitable environmental conditions for their growth.

One of the environmental conditions that supports fungal growth is soil pH. The pH values of six soil samples from the Cikaniki Station area are shown in Figure 5. The relatively acidic pH conditions support

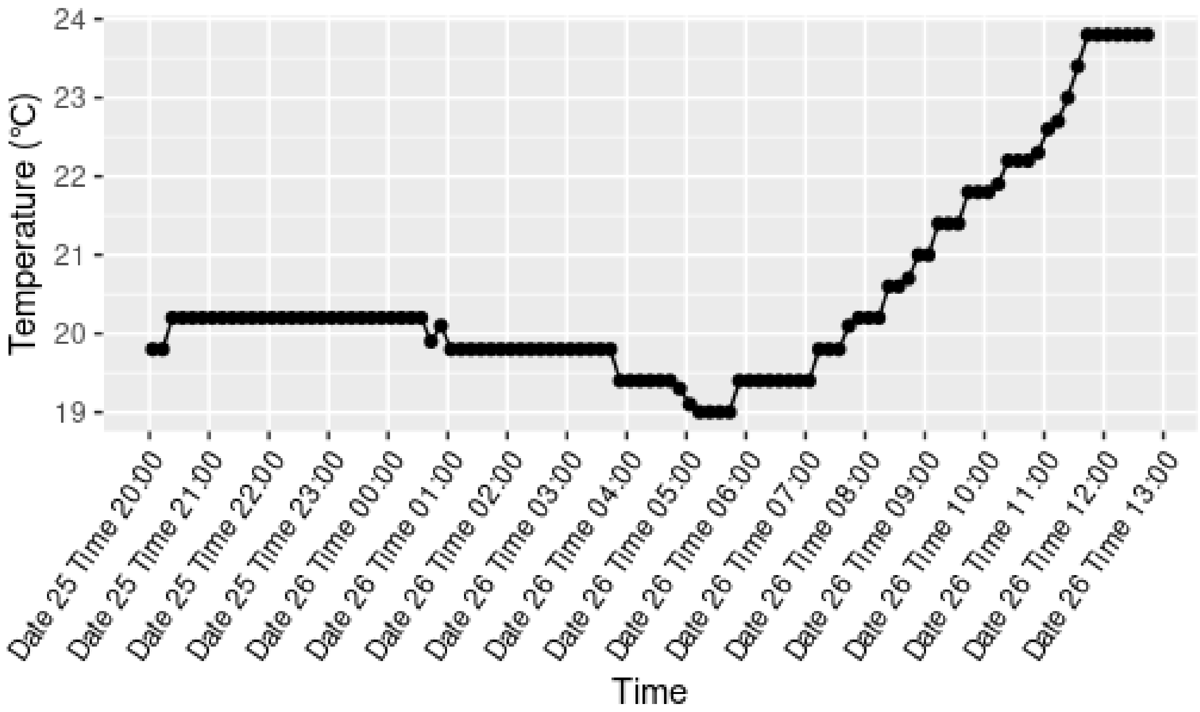


Figure 6. Real-time air temperature (°C) graph of bioluminescent fungi habitat

the growth of bioluminescent fungi, contributing to a rich and diverse ecosystem. Several samples fall within the optimal pH range for fungal growth, which is between pH 4.5 and 8 (Noerhandayani *et al.* 2022). According to Hidayat *et al.* (2020), fungi tend to grow better in acidic conditions, as such environments align with the slightly weaker metabolism of fungi. Fungi grow well at around pH 5.5 because they can effectively stabilize their intracellular pH. Therefore, maintaining a suitable pH level is essential for optimal enzyme activity in fungi.

Based on research conducted by Noverita *et al.* (2018) on Saktu Island, Pulau Seribu, North Jakarta, the habitat of bioluminescent fungi (*Mycena chlorophos*) was found on dead and decayed branches and twigs, as well as on forest floor litter, with a soil pH of 6.5. In a study by Armadhan *et al.* (2023) in the karst forest of Kalipoh Village, Kebumen Regency, *Mycena chlorophos* was found on decaying wood trunks with a soil pH of 7.

Bioclimate Characteristics

GHSNP is a conservation area located in West Java. The area encompasses lowland rainforest, submontane forest, and montane forest ecosystems on the island of Java, featuring undulating, hilly, and mountainous topography with elevations ranging from 500 to 2211 meters above sea level (Istomo & Sari, 2019; Polosakan & Alhamd, 2012). According to the Schmidt and Ferguson (1951) climate classification, GHSNP falls under climate type B, which experiences 1.5 to 3 dry months annually. The region receives an annual rainfall of approximately 4000–6000 mm. The rainy season, with rainfall ranging from 400–600 mm per month, occurs from October to April, while the dry season, with around 200 mm of rainfall per month, spans from May to September. The average monthly temperature is 31.5 °C, with a minimum of 19.7 °C and a maximum of 31.8 °C, and the area maintains an average relative humidity of 88% (Hartono *et al.* 2007).

Both species of bioluminescent fungi identified in this study were distributed in areas with daily air temperatures ranging from 20 to 24 °C (Figure 6). The tropical rainforest that serves as their habitat features dense vegetation, which limits sunlight penetration. The low light intensity reaching the forest floor prevents significant increases in soil temperature (Hasanuddin, 2014). These conditions are suitable for the growth of macroscopic fungi, which generally thrive in environments with temperatures between 22 and 35 °C (Arif *et al.* 2007). The ambient temperature around the habitat of bioluminescent fungi is influenced by the presence of shading vegetation. These fungi were found on substrates such as litter layers, dead woody twigs, and twigs around the litter, all located beneath

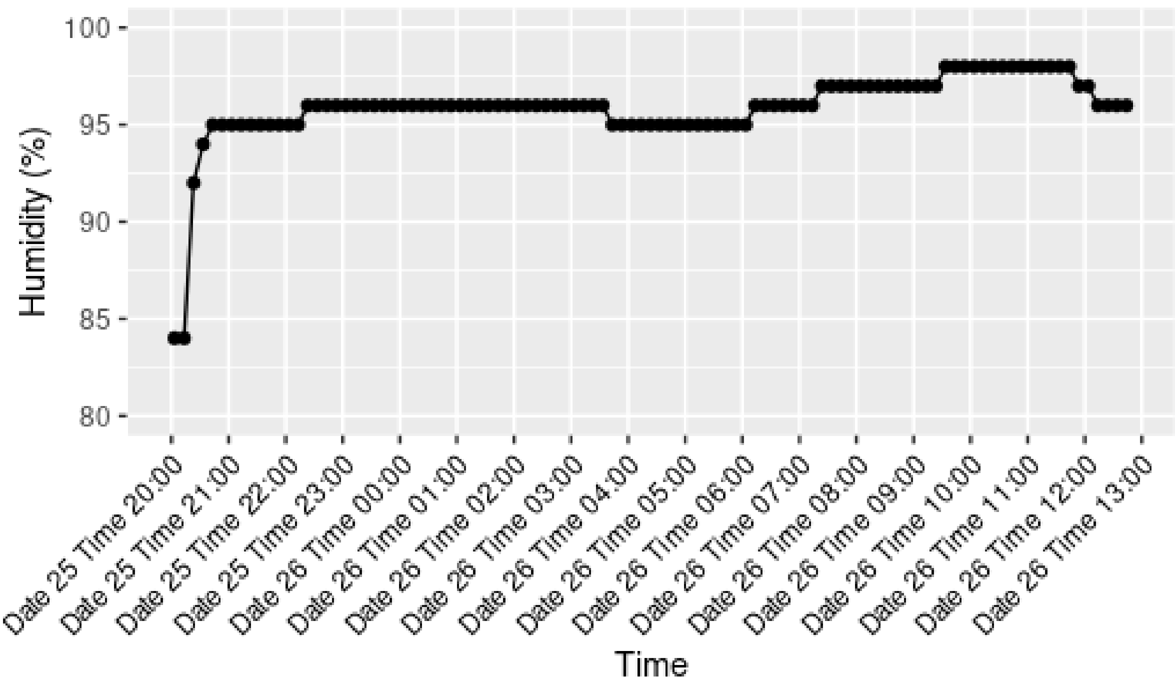


Figure 7. Real-time air humidity (%) graph of bioluminescent fungi Habitat

vegetative cover. Shaded conditions help maintain suitable air temperature and humidity levels necessary for the growth of bioluminescent fungi. This is consistent with the findings of Irpan and Prasaja (2021), who reported that fungi from the family Mycenaceae, which grow in colonies on shaded decaying wood, thrive in such environments that provide favorable conditions for fungal life.

Another abiotic factor influencing fungal growth is humidity. The recorded air humidity levels around the growth sites of both bioluminescent fungi species ranged from 84% to 98% (Figure 7). This level of air humidity is closely related to the transpiration process of vegetation surrounding the habitat of bioluminescent fungi. Water vapor produced through transpiration is not freely released due to the broad canopy cover, resulting in high air humidity around the vegetation (Hasanuddin 2014). This also contributes to moist soil surface conditions, which are favorable for the growth of bioluminescent fungi. The air humidity recorded during the nighttime observation was 85% and continued to increase until the end of the daytime observation, reaching 96%. According to the study by Irpan and Prasaja (2021), Various fungal species found in the GHSNP area, including fungi from the family *Mycenaceae*, grow in environments with air humidity ranging from 70% to 100%. This indicates that GHSNPP provides a suitable habitat for the growth of bioluminescent fungi.

Shading Vegetation

The shading vegetation in the habitat of bioluminescent fungi was analyzed using hemispherical photography to determine the canopy openness and Leaf Area Index (LAI) values. The analysis was conducted in two different observation plots: plot 1 with one replicate (P11), and plot 2 with two replicates, plot 2 replicate 1 (P21) and plot 2 replicate 2 (P22). Each replicate within the plots was analyzed using different threshold settings, adjusted according to the hemisphere characteristics of each plot. LAI was analyzed in two forms: LAI 4-ring and LAI 5-ring. The results of the hemispherical photography analysis for the bioluminescent fungi habitat in plots 1 and 2 are presented in Table 6 and Table 7.

Tables 6 and 7 also present the values of canopy openness, threshold, and LAI in the habitat of bioluminescent fungi. Canopy openness reflects the degree of canopy cover formed by trees or vegetation. This value is inversely related to vegetation density, meaning the lower the canopy openness, the denser the surrounding vegetation. Conversely, a higher canopy openness indicates lower vegetation density, suggesting that the vegetation around the habitat of bioluminescent fungi is sparse or less compact.

Canopy openness analysis was conducted using two versions of hemispherical photography: the circular version and the rectangular version, with one replicate in plot 1 and two replicates in plot 2. Differences were observed in canopy openness values between the circular and rectangular versions. In the rectangular version, canopy openness at P11 was higher than at P21 and P22, whereas in the circular version, canopy openness at P11 was lower than at P22 but higher than at P21. This discrepancy may be due to the circular hemispherical photography covering a smaller area compared to the rectangular version, which likely has a wider coverage.

The higher canopy openness value at P11 in the rectangular hemispherical photography indicates a more open canopy cover, which results in increased light intensity. A more open canopy allows more light to penetrate, thereby reducing humidity and decreasing the density of bioluminescent fungi in the population. Consequently, the individual density in plot 1 is lower compared to that in plot 2, as shown in Tables 6.1 and 7.1 below. These findings on canopy openness align with the study by Fikri *et al.* (2023), which reported that areas with more open canopy cover have higher light

Table 6. Hemispherical photography analysis of the bioluminescent fungi habitat (circular version)

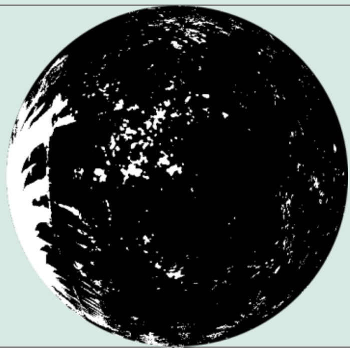
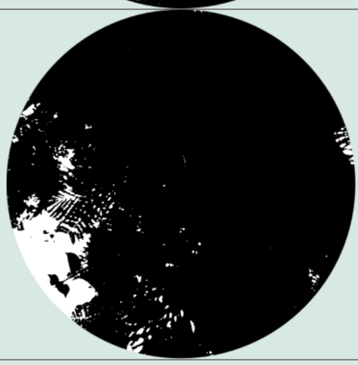
No.	Photo	Plot	Threshold	Canopy Openness (%)	LAI 4 Ring	LAI 5 Ring
1		P11	128	9,97	4,31	3,21
2		P21	226	8,02	3,33	2,86
3		P22	218	10,97	3,84	3,32

Table 7. Hemispherical photography analysis of the bioluminescent fungi habitat (rectangular version)

No.	Photo	Plot	Threshold	Canopy Openness (%)	LAI 4 Ring	LAI 5 Ring
2		P21	188	13,82	2,47	2,15
3		P22	223	7,56	4,79	3,84
1		P11	212	13,69	3,4	2,86

intensity than areas with denser canopy cover. Budiarti and Nasrullah (2014) also stated that canopy cover affects surrounding temperature and humidity, the higher the canopy cover percentage, the lower the air temperature and the higher the humidity, and vice versa.

In addition to canopy openness, the density of individuals in the habitat of bioluminescent fungi is also influenced by the Leaf Area Index (LAI), with LAI values for P11, P21, and P22 shown in Tables 6 and 7 above. LAI measurements in each plot aim to assess canopy density, where a higher LAI value indicates denser tree canopy and greater interception of solar radiation. According to Rushayati *et al.* (2012), the minimum adequate LAI value in tropical regions is 0.19. Based on data analysis, the LAI values in each plot replicate exceeded 0.19, indicating that the habitat conditions for bioluminescent fungi are suitable and favorable.

Previous research by Hardina *et al.* (2019), which assessed habitat conditions against bird community trends in the GHSNP, also found LAI values exceeding 0.19, exactly around 4.50 and above. Based on Turner *et al.* (1999) classification, LAI values within this range are classified as primary forest. An increase in LAI creates a microclimate characterized by lower air temperatures. Additionally, LAI shows a positive linear relationship with humidity, the higher the LAI, the higher the humidity level (Putra *et al.* 2022).

Habitat Protection Recommendations

Fungi serve as key agents in the forest carbon cycle by decomposing dead wood, which harbors one-third of forest biodiversity (Shelton *et al.* 2021). As functional microorganisms in soil biogeochemical modeling, fungi play a crucial role in degrading complex substrates such as lignin and hemicellulose, thus contributing significantly to carbon and nitrogen cycles (Abramoff and Finzi, 2022). Important forest fungal groups, like wood-decaying fungi, act as mutualists essential for plant growth and also function as pathogens (Iapichino *et al.* 2019). For example, *Pleurotus djamor* exhibits spontaneous electrical activity that may reflect mycelial growth within substrates, nutrient and metabolite transport, and network communication. This highlights the complex biological functions of fungi in information processing and network regulation within forest ecosystems (Dehshibi and Adamatzky, 2020). Given their vital roles in sustaining forest ecosystems, fungi such as bioluminescent species require conservation efforts to maintain their stable presence within their habitats.

Physically, the population of bioluminescent fungi in Gunung Halimun Salak National Park is protected by the area's conservation status, even though the species found are not currently threatened. *Mycena* fungi naturally thrive in habitats with suitable conditions such as air temperature, light intensity, air humidity, and substrate availability. Although there is no specific protection for these fungi, cultivation can be carried out in habitats rich in leaf litter to help preserve heterotrophic myco-plants symbiotic with *Mycena* (Higaki *et al.* 2017). The sites where these fungi are found are accessible to tourists, so high foot traffic and physical contact may disrupt the species' existence. Similarly, urbanization and extensive land use have displaced fungal habitats (Dahlberg *et al.* 2010).

Protected areas should provide guides, such as infographics or tour guides, to accompany visitors to fungal habitats. Additionally, conservation efforts can incorporate AI modeling to identify, track populations, and detect changes in fungal distribution due to climate change (Kellenberger *et al.* 2022). In addition to conserving the target bioluminescent fungi species, it is also important to protect other species associated with them. Based on this study, several tree species are linked to these fungi, as their presence provides suitable leaf litter composition for the fungi's growth. These trees include saninten (*Castanopsis argentea*), burunungguI (*Blumeodendron elateriospermum*), pasang reueuy (*Lithocarpus* sp.), rasamala (*Altingia excelsa*), and ki sauheun (*Orophea hexandra*). Ongoing assessment of fungal species is necessary, given the vast diversity of fungi and the continuous discovery of new species.

Conservation becomes effective when it targets the right species, especially those confirmed as threatened through proper assessments. Data collection on fungal presence, which forms the basis for such assessments, can be facilitated by engaging citizen scientists across various regions, with expert panels verifying data accuracy. Essentially, ecological and distribution studies like this research are themselves conservation efforts. Enhancing understanding of a species helps identify the habitats that need protection and pinpoint biodiversity hotspots important for fungi.

CONCLUSIONS

Bioluminescent fungi in GHSNP exhibit specific ecological relationships in their growth, thriving in tropical rainforest habitats with substrates such as dead woody twigs and litter layers. The bioclimatic characteristics of their habitat include a pH range of 5.5–6.8, optimal air temperatures between 20–24 °C, and air humidity levels ranging from 85% to 99%, supported by a Leaf Area Index (LAI) above 0.19 and low canopy openness values. The distribution of bioluminescent fungi was lower in observation plot 1 compared to plot 2. Plot 2 had denser vegetation, resulting in higher humidity and greater fungal abundance. The species found in this study were *Mycena* sp. and an unidentified Species X. These ecological characteristics indicate that bioluminescent fungi cannot grow just anywhere—they require specific environmental conditions. Therefore, to sustain their existence and promote conservation, efforts must focus not only on the target species but also on other species associated with their habitat.

ACKNOWLEDGEMENTS

We would like to express our gratitude to the IPB SSRS Association and Gunung Halimun Salak National Park (GHSNP) for facilitating this research, as well as to the various literature sources and macrofungi experts for their valuable contributions during the analysis of bioluminescent fungi in this study.

REFERENCES

Abramoff RZ, Finzi AC. 2022. Similarities and differences in the sensitivity of Soil Organic Matter (SOM) dynamics to microbial parameters across ecosystem models. arXiv:2210.16417. Tersedia di:

https://arxiv.org/abs/2210.16417.

Arif A, Musrizal M, Tutik K, Vitri H. 2007. Isolasi dan identifikasi jamur kayu dari Hutan Pendidikan dan Latihan Tabo-Tabo Kecamatan Bungoro Kabupaten Pangkep. *Jurnal Perennial.* 3(2): 49 – 54.

Armadhan WS, Sari SP, Aji MYMB, Permatasari DP, Amalia BW, Berlin GE, Aszar AS, Indrawan M, Pradhan P, Setyawan AD. 2023. The macrofungal diversity and its potential from the karst forest of Kalipoh Village, Kebumen District, Indonesia. *Asian Journal of Forestry.* 7(2):99 – 106. doi:10.13057/asianjfor/r070204

Arya CP, Ratheesh S, Pradeep CK. 2021. New record of luminescent *Mycena chlorophos* (Mycenaceae) from Western Ghats of India. *Studies in Fungi.* 6(1):507 – 513.

Budiarti T, Femy N, Nasrullah. 2014. Pengaruh tata hijau terhadap suhu dan kelembaban relatif udara pada Balai Besar Pengembangan Mekanisasi Pertanian, Serpong. *Jurnal Lanskap Indonesia.* 6(2):21 – 28. doi:10.29244/jli.v6i2.16583.

Dahlberg A, Genney DR, Heilmann-Clausen J. 2010. Developing a comprehensive strategy for fungal conservation in Europe: current status and future needs. *Fungal Ecology.* 3(2):50 – 64.

Dehshibi MM, Adamatzky A. 2020. Electrical activity of fungi: Spikes detection and complexity analysis. arXiv:2008.10276. Available on: https://arxiv.org/abs/2008.10276.

Diningestu RF, Mahmudah. 2024. Analisis *time series* ARIMA untuk memprediksi jumlah peserta KB baru pasca persalinan di Jawa Timur. *Media Gizi Kesmas.* 13(1):85 – 92. doi:10.20473/mgk.v13i1.2024.85-92 .

Fikri N, Rahman DA, Santoso N. 2023. Carrying capacity estimation and habitat suitability of *Sumatran elephan*t in Datuk Gedang Wildlife Corridor, Bukit Tigapuluh Landscape, Jambi, Indonesia. *Biodiversitas.* 24(10):5548 – 5557. doi: 10.13057/biodiv/d241036.

Hani A, Widyaningsih TS, Damayanti RU. 2014. Potensi dan pengembangan jenis-jenis tanaman anggrek dan obat-obatan di jalur wisata loop trail Cikaniki-Citalahab Taman Nasional Gunung Halimun-Salak. *Jurnal Ilmu Kehutanan.* 8(1):42 – 49.

Hardina K, Mulyani YA, Mardiastuti A. 2019. Komunitas burung pada pegunungan bawah dan sub-pegunungan di Taman Nasional Gunung Halimun Salak. *JPSL.* 9(3): 736-745. doi: 10.29244/jpsl.9.3.736-745.

Hartono T, Kobayashi H, Widjaya H, Suparmo M. 2007. *Taman Nasional Gunung Halimun Salak: Menyingkap Kabut Gunung Halimun Salak.* Bogor: Gunung Halimun Salak National Project-JICA.

Hasanuddin. 2014. Jenis jamur kayu makroskopis sebagai media pembelajaran biologi (studi di TNGL Blangjerango Kabupaten Gayo Lues). *Jurnal Biotik.* 2(1):1 – 76.

Hasibuan RS, Jenuarista ST. 2019. Distribution of mushrooms in the Resort Cikaniki at Mount Halimun Salak National Park. *ICTS.* 394(1):1 – 10.

Hidayat T, Syauqi A, Rahayu T. 2020. Uji antagonis jamur *Gliocladium* sp dalam menghambat pertumbuhan jamur *Fusarium* sp penyebab penyakit layu pada tanaman pisang (*Musa paradisiaca* L.). *e-Jurnal Ilmiah BIOSAINTROPIS.* 5(2):59 – 65.

Higaki K, Rammitsu K, Yamashita Y, Yukawa T, Ogura-Tsujita Y .2017. A method for facilitating the seed germination of a *Mycoheterotrophic orchid*, *Gastrodia pubilabiata*, using decomposed leaf litter harboring a basidiomycete fungus, *Mycena* sp. *Bot Stud.* 58(59):1 – 7. doi: 10.1186/s40529-017-0214-6.

Iapichino M, Wang YW, Gentry S, Pringle A, Seminara A. 2019. A precise relationship among Buller's drop, ballistospore and gill morphology enables maximal packing of spores within gilled mushrooms. *arXiv*:1904.08127. doi:10.48550/arXiv.1904.08127.

Irpan AM, Prasaja D. 2021. Keanekaragaman jamur makroskopis di jalur pendakian Kawah Ratu Taman Nasional Gunung Halimun Salak. *Jurnal Penelitian Ekosistem Dipterokarpa.* 7(1):35 – 48.

Istomo, Sari PN. 2019. Penyebaran dan karakteristik habitat jenis rasamala (*Altingia excelsa* Noronha) di Taman Nasional Gunung Halimun Salak. *Journal of Natural Resources and Environmental Management.* 9(3): 608 – 625.

Kellenberger B, Doshi S, Tuia D. 2022. BioTrove: A Large Curated Image Dataset Enabling AI for Biodiversity. *arXiv*:2406.17720. Tersedia di: https://arxiv.org/abs/2406.17720.

Lee SML. 2022. The status of bioluminescent fungal species in Singapore. *Nature in Singapore* (1Supl 1).

Noerhandayani Y, Turnip M, Ifadatin S. 2022. Keanekaragaman jamur makroskopis di perkebunan kelapa sawit Desa Sebayan Kabupaten Sambas. *Agroprimatech* 6(1):17 – 24 .

Noverita, Nabilah, Siti FY, Yudistari. 2018. Jamur makro di Pulau Saktu Kepulauan Seribu Jakarta Utara dan potensinya. *Jurnal Mikologi Indonesia.* 2(1):16 – 29.

Oliveira AG, Desjardin DE, Perry BA, Stevani CV. 2012. Evidence that a single bioluminescent system is shared by all known bioluminescent fungal lineages. *Photochem Photobiol Sci.* 11(5):848 – 852. doi: 10.1039/c2pp25032b.

Oliviera AG, Stevani CV, Waldenmaier HE, Viviani V, Emerson JM, Loros JJ, Dunlap JC. 2015. Circadian control sheds light on fungal bioluminescence. *Current Biology.* 25(7):964 – 968.

Polosakan R, Alhamd L. 2012. Keanekaragaman dan komposisi jenis pohon di Hutan Pameumpeuk Taman Nasional Gunung Halimun Salak Kabupaten Sukabumi. *Jurnal Teknologi Lingkungan edisi khusus.* 53 – 59.

Putra BU, Krisnandik AGK, Dharmadiatmika IMA. 2022. Pengaruh kombinasi kerapatan kanopi pohon terhadap kenyamanan termal di Lapangan Puputan Margarana, Denpasar. *Jurnal Lanskap Indonesia*. 14(1):16 – 21. doi:10.29244/jli.v14i1.38646.

Putra IP. 2020. Studi taksonomi dan potensi beberapa jamur liar di Pulau Belitong. *Justek: Jurnal Sains dan Teknologi*. 3(1):24 – 31.

Putra IP, Mardiyah ERA, Amalia NS, Mountara A. 2017. Ragam jamur asal serasah dan tanah di Taman Nasional Ujung Kulon Indonesia. *Jurnal Sumberdaya Hayati*. 3(1):1 – 7.

Qurniawati M, Ratnawulan. 2021. Optimization of the optimum condition of mushroom light excitation (Neonothopanus sp) bioluminescence. *Eksakta: Berkala Ilmiah Bidang MIPA*. 22(1):1 – 9.

Rushayati SB. 2012. Hubungan antara indeks luas daun dengan iklim mikro dan indeks kenyamanan. *Media Konservasi*. 17(3):143 – 148 . doi:10.29243/medkon.17.3.%p.

Schmidt FH, Ferguson JHA. 1951. Rainfall types based on wet and dry period ratios for Indonesia with Western New Guinea.

Sharma D, Gupta D. 2024. Bioluminescence in mushrooms. *Agri Journal World*. 4(6): 12 – 19.

Shelton JA, Polewski P, Yao W, Heurich M. 2021. A hybrid convolutional neural network/active contour approach to segmenting dead trees in aerial imagery. arXiv:2112.02725. Tersedia di: https://arxiv.org/abs/2112.02725.

Teranishi K. 2016. Localization of the bioluminescence system in the pileus of *Mycena chlorophos*. *Luminescence*. 31: 594 – 599. doi: 10.1002/bio.3001.

Turner DP, CohenWB, KennedyRE, FassnachtKS, Brigss JM. 1999. Relationship between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. *Remote Sensing Environment*.70:52-68.

Wati R, Noverita N, Setia TM. 2019. Keanekaragaman jamur makroskopis di beberapa habitat kawasan Taman Nasional Baluran. *Jurnal Biologi*. 12(2): 171 – 180.