

Article

Effects of Different Colored Films on the Microenvironment and Development of *Morchella septimelata* and *Morchella sextelata*

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Abstract

Morchella spp. are rare and highly valued edible fungi that often exhibit unstable yield and quality under protected cultivation due to inadequate regulation of the light and temperature microenvironment. Colored films can effectively optimize these conditions. In this study, the effects of six colored film treatments—white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM), and silver-black film (SBM)—on the microenvironment and development of *Morchella septimelata* and *M. sextelata* were investigated. The results showed that the BM treatment improved the microenvironment and promoted *Morchella* development. BM exhibited high transmittance, enhancing light intensity and increasing accumulated air and soil temperatures. It also led to the production of the greatest number of mature fruiting bodies, with 46 per square meter for *M. septimelata* and 54 per square meter for *M. sextelata*. Agronomic traits were also superior under the BM treatment, with pileus lengths of 82.97 mm for *M. septimelata* and 70.76 mm for *M. sextelata*. Compared with WM, BM significantly increased the weight of a single fruiting body and yield by 12.23% and 20.86% for *M. septimelata* and by 18.14% and 25.34% for *M. sextelata*, respectively. BM also significantly increased crude fiber content by 16.92% in *M. septimelata* and 2.63% in *M. sextelata*. RM significantly increased crude polysaccharide content by 47.42% in *M. septimelata* and by 44.12% in *M. sextelata*. This study indicated that BM was the preferred choice for *Morchella* protected cultivation.

Keywords: morel mushrooms; soil temperature; agronomic traits; nutritional quality



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1. Introduction

Morchella spp. belong to the phylum Ascomycota and are rare edible fungi characterized by irregular depressions and folds on their pilei that resemble sheep's reticula [1]. They have tender flesh and a unique flavor and are rich in polysaccharides [2], amino acids [3], vitamins, and various trace elements [4]. Additionally, because they possess medicinal properties, such as antioxidant and immune-enhancing activities [5,6], *Morchella* spp. hold extremely high commercial value and occupy a crucial position in the market. Morels, renowned as among the world's most valuable and rare edible mushrooms, are widely distributed across temperate regions of Europe, Asia, and North America [7,8]. China is the

largest morel producer, with the earliest commercial cultivation of these species starting in 2012 [9]. Since then, the cultivation area has expanded rapidly, growing from approximately 67 ha to approximately 29,800 ha [10]. However, the widely cultivated *Morchella septimelata* and *M. sextelata* exhibit narrow adaptability to ecological environments, and their cultivation techniques are not yet fully mature. Inadequate regulation of microenvironments such as light and temperature often leads to unstable yields and substantial quality differences, directly restricting the large-scale development of protected cultivation [11].

Mulch film coverage effectively improves the light environment and regulates air and soil temperatures, significantly affecting crop growth and the soil ecosystem [12]. In apricot orchards, the light environment is significantly optimized by reflective and heat-insulating mulch films, with light intensity increasing by 161.04–208.71% and reflectivity increasing by 2.6–3.3 times to promote fruit ripening. Moreover, soil temperature and humidity are effectively regulated by waterproof and breathable mulch films, and the nutrient content of the fruit improves accordingly [13]. With respect to strawberry production, soil temperature is significantly increased by black and red mulch films, whereas it is maintained at a relatively low level by white films, and field humidity is stably maintained by all three types of film [14]. In *Platostoma palustre* cultivation, soil temperature in the 0–20 cm layer is elevated by black and red mulch films compared with white films, and the lowest temperature in this layer is observed with white mulch films, rendering them unsuitable for the growth of *P. palustre* [15]. Under nonflooded rice growth conditions, soil temperature in the 0–25 cm layer during the growth period is increased by black, bicolor and transparent plastic mulch films; black and bicolor plastic mulch films effectively increase rice yield, whereas transparent plastic mulch films easily induce high-temperature stress, usually leading to yield reduction [16]. With respect to protected tomato production, daily air temperature accumulation is greatest under silver mulch films and lowest under black films; all mulch films reduce water evaporation and stabilize soil temperature in protected growing systems [17].

Morchella field cultivation has developed rapidly, and plastic mulch cultivation is now widely adopted [18]. Mulch films of different colors absorb and reflect light of different wavelengths and thus modify temperature and light conditions in the cultivation environment [19]. Many environmental factors, such as temperature and light quality, control the growth and development of edible fungi [20]. *Auricularia heimuer* has the highest mycelial growth rate and fresh weight at 35 °C, with mycelial growth inhibited at 15 °C and severely suppressed at 45 °C, potentially even inducing mycelial mortality [21]. The optimum growth temperature of *Coprinellus saccharinus* mycelium is 25 °C; its growth is significantly inhibited at 15 °C and 35 °C, and a temperature difference of 2–4 °C is required for primordium induction [22]. The optimum growth temperature of *Bjerkandera adusta* mycelium is 30 °C; the optimum temperature for mycelial colonization is 25 ± 1 °C, and a diurnal temperature variation of 25–30 °C during the day and 16–18 °C during the night is required for primordium induction [23]. Red light is the optimal light quality for primordium formation and fruiting body development in *Pleurotus eryngii* [24]. Blue light is the optimal light quality for regulating the color, agronomic traits, and antioxidant capacity of *Sarcomyxa edulis* [25]. Green light is beneficial to the growth and nutrient accumulation of *Ganoderma lingzhi* [26]. Blue light irradiation of *Lentinula edodes* mycelial sticks enhances fruiting body yield, agronomic traits, and textural quality [27]. Blue light irradiation at 800–1200 lx delays spore release, reduces respiration, maintains energy levels, and preserves the contents of umami amino acids and umami nucleotides in *L. edodes* [28]. Yellow light treatment helps improve the color, biomass, and adenosine content of *Cordyceps militaris* stroma, whereas white light increases polysaccharide content [29].

The growth and development of *Morchella* spp., typical soil saprophytic fungi, are highly sensitive to microenvironmental factors such as light quality and temperature. Colored films have been widely studied in crop production, but their application in the production of other edible fungi, especially soil saprophytic species, remains unexplored. Existing studies on colored films in *Morchella* have focused solely on yield [30]. No research has been conducted on blue film mulching, and a systematic analysis of the spectral characteristics of different colored films is lacking. In this study, *M. septimelata* and *M. sextelata* were used as experimental materials. Six colored film treatments were applied: white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM), and silver-black film (SBM). The cultivation microenvironment, number of fruiting bodies, agronomic traits, yield, and nutritional quality were systematically measured. Microenvironmental parameters were then integrated with developmental and quality indicators, and correlation analysis was performed to elucidate the potential mechanisms through which different light quality environments affect *Morchella*. These findings provide a theoretical and practical basis for the protected cultivation of *Morchella*.

2. Materials and Methods

2.1. Experimental Materials

Test strains included *M. septimelata* 'G18' and *M. sextelata* 'G5', both preserved in the Edible Fungi Laboratory of Hebei Agricultural University. The PDA medium contained 200 g potato infusion, 20 g glucose, 20 g agar, and 1 L distilled water. The formulations for stock culture and spawn included 55% wheat grains, 17.5% corn cobs, 17.5% wood chips, 8% wheat bran, 1% lime, and 1% gypsum.

2.2. Experimental Design

In this experiment, six colored film treatments were included: white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM), and silver-black film (SBM), all made of polyethylene with a uniform thickness of 0.01 mm (Zhejiang Jialemei Horticultural Technology Co., Ltd., Shaoxing, China) (Figure 1). The experiment adopted a randomized complete block design. Sowing was conducted on 30 November 2024 at Xibaituo Village, Gaoling Town, Wangdu County, Baoding City, Hebei Province. Small arch sheds were built, with dimensions of 3 m × 2 m × 0.6 m (length × width × height). The tops of the sheds were covered with the respective colored films. Each plot had an area of 6 m² (3 m × 2 m). Exogenous nutrient bags were placed on 15 December 2024, after the mycelia had fully colonized the soil surface. Fruiting induction irrigation was applied on 18 February 2025. Environmental monitoring and growth surveys were initiated on 28 February 2025. During data collection, three technical replicates were performed for each biological replicate.

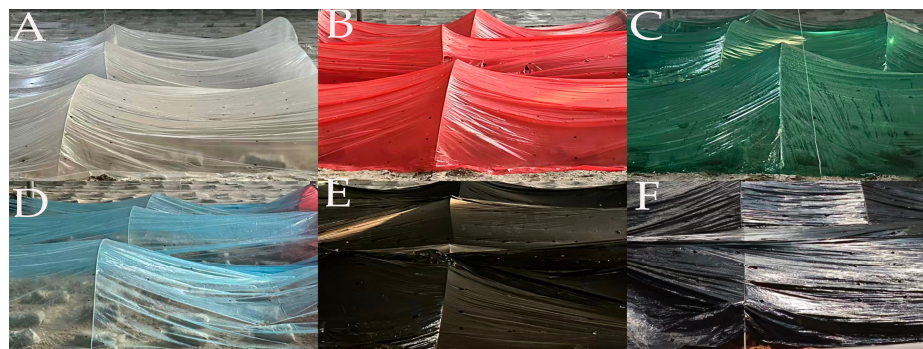


Figure 1. Different colored film treatments: (A) white film (WM), (B) red film (RM), (C) green film (GM), (D) blue film (BM), (E) black film (BKM), and (F) silver-black film (SBM).

2.3. Measured Indicators and Methods

2.3.1. Microenvironmental Parameters

Transmittance was measured at 10 cm above the soil surface using a QE 6500 fiber-optic spectrometer (Shanghai Bose Intelligent Technology Co., Ltd., Shanghai, China). Light intensity was determined at 10 cm above the soil surface using an OHSP-350S spectroradiometer (Hangzhou Hongpu Optochromatic Technology Co., Ltd., Hangzhou, China). Air temperature and humidity beneath the mulch film and soil temperature were monitored using a remote environmental monitor S21A-2700 (Xuzhou Fala Electronic Technology Co., Ltd., Xuzhou, China). Air temperature probes were placed 10 cm above the soil surface to collect air temperature and humidity data, and soil temperature probes were placed at a soil depth of 15 cm to collect soil temperature data. Data were recorded every 5 min, and continuous measurements were taken for 30 days. Moreover, the average and accumulated values of air and soil temperatures, as well as average humidity, were calculated for subsequent analysis [30]. The accumulated air temperature and accumulated soil temperature were calculated as follows:

$$\text{Accumulated air temperature (accumulated soil temperature)} = \sum T_i$$

where T_i is the temperature recorded at 5 min intervals. Accumulated temperature is a common metric used to quantify thermal time or heat accumulation over a period and has been widely applied in agricultural and microbiological studies [31].

2.3.2. Number of Fruiting Bodies

As illustrated in Figure 2, the number of fruiting bodies at the primordium, pinhead and maturation stages of *M. septimelata* and *M. sextelata* was recorded per square meter (m^2).

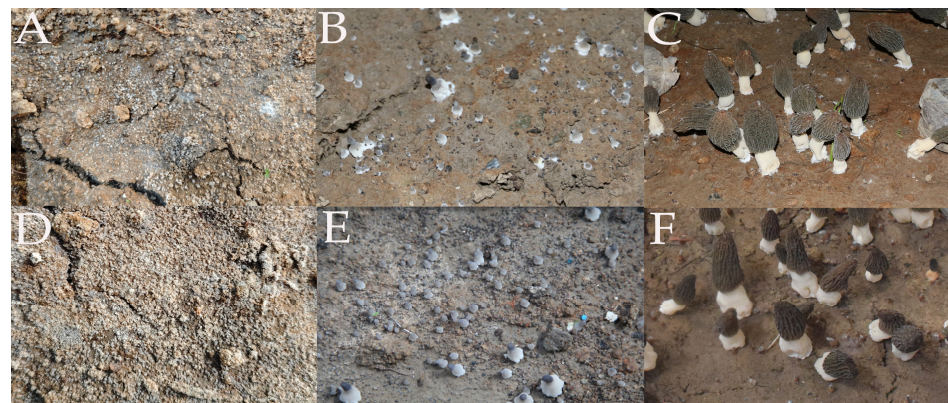


Figure 2. *M. septimelata* at the (A) primordium stage, (B) pinhead stage, and (C) maturation stage; *M. sextelata* at the (D) primordium stage, (E) pinhead stage, and (F) maturation stage.

2.3.3. Agronomic Traits and Yield of Fruiting Bodies

At the maturation stage of fruiting bodies, ten fruiting bodies were randomly selected for measurement. The length and width of the pileus and stipe were measured using a digital Vernier caliper DWKC-2013 (Delixi Electric Co., Ltd., Wenzhou, China), and the ratio of the pileus length to the stipe length was calculated. The weight of a single fruiting body and the yield per square meter (m^2) were determined using an LC-FA004 electronic balance (Shanghai Lichen Instrument Technology Co., Ltd., Shanghai, China).

2.3.4. Determination of Nutritional Quality

Fruiting bodies of *Morchella* from different colored film treatments were collected and dried in a dark, constant-temperature oven at 55 °C. The dried samples were ground, sieved

through a 100-mesh standard sieve, and collected as a fine powder. The powdered samples were subsequently used for the determination of crude protein [32], polysaccharide [33], and fiber [34] contents. Three parallel replicates were established for each treatment to ensure data reliability.

2.4. Data Analysis

The experimental data were analyzed with IBM SPSS Statistics 27.0. Differences between treatments were determined using the LSD multiple range test at a significance level of $p < 0.05$. Data are presented as the mean $\pm$ standard deviation (SD), and plotting was conducted with Origin 2024.

3. Results

3.1. Effects of Different Colored Films on the Microenvironment

All colored films exhibited transmittance within the visible light spectrum, although with variations across different film types (Figure 3). Compared with the WM treatment, the BM treatment resulted in the highest transmittance of 92% at 405 nm, and its transmittance in the 400–572 nm range was higher. The RM treatment resulted in a relatively high transmittance of 77–80% in the 600–700 nm range, whereas the GM treatment resulted in a moderate transmittance of 59–63% in the 450–550 nm range. By contrast, the BKM and SBM treatments resulted in low transmittance across the entire visible spectrum. Among all the treatments, the BM treatment resulted in the highest transmittance for *Morchella*, whereas the BKM and SBM treatments resulted in the lowest transmittance.

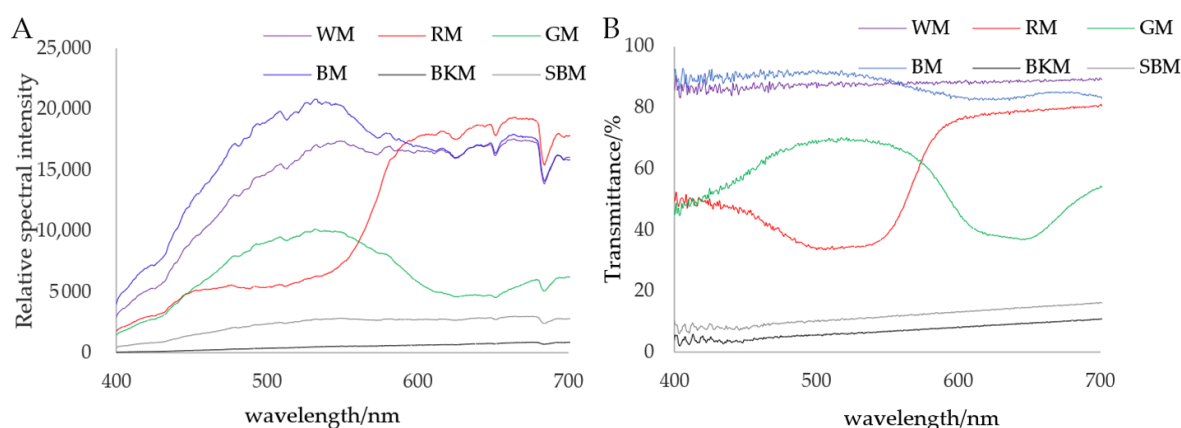


Figure 3. Different colored films of (A) relative spectral intensity (B) transmittance. Note: white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM), silver-black film (SBM).

Different colored film treatments affected light intensity. As shown in Figure 4, across different times of day, the WM, RM, GM, BM, and SBM treatments reached maximum light intensity at 10:30, and all six treatments reached minimum intensity at 17:30. Moreover, the BM treatment maintained the highest light intensity throughout the day, reaching a peak of 1898.22 lx at 10:30. This value was significantly greater than those of the WM (1250.18 lx), RM (631.32 lx), and GM (849.49 lx) treatments. By contrast, the BKM and SBM treatments resulted in the lowest light intensities of 58.45 lx and 76.44 lx, respectively.

In addition, the effects of different colored film treatments on average humidity, accumulated air temperature, average air temperature, accumulated soil temperature, and average soil temperature were analyzed. As shown in Figure 5, the results indicated that there were no significant differences in average humidity among the RM, GM, BM, and SBM treatments. Air and soil temperatures changed significantly under the different colored film treatments. The accumulated air temperature in the BM treatment was 92,013.9 °C,

which was significantly greater than that in the other colored film treatments. Additionally, the accumulated soil temperature in the BM treatment was 76,661.4 °C, which was also significantly greater than that in the other treatments. The BM treatment resulted in the highest average air temperature, whereas the GM treatment resulted in the lowest average air temperature. Thus, the BM treatment significantly increased accumulated air and soil temperatures.

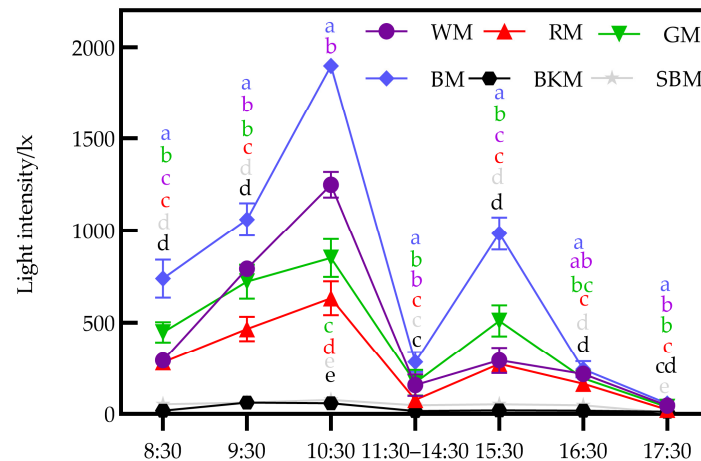


Figure 4. Effects of different colored film treatments (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on light intensity. Note: The area (11:30–14:30) indicates the period when the sheds were covered with sunshade cloth to prevent high-temperature stress; therefore, the light intensity remained unchanged during this period. Significant differences are compared among different mulch treatments at each time point. Values labeled with different letters in the graph are significantly different according to the least significant difference (LSD) multiple range test ($p < 0.05$).

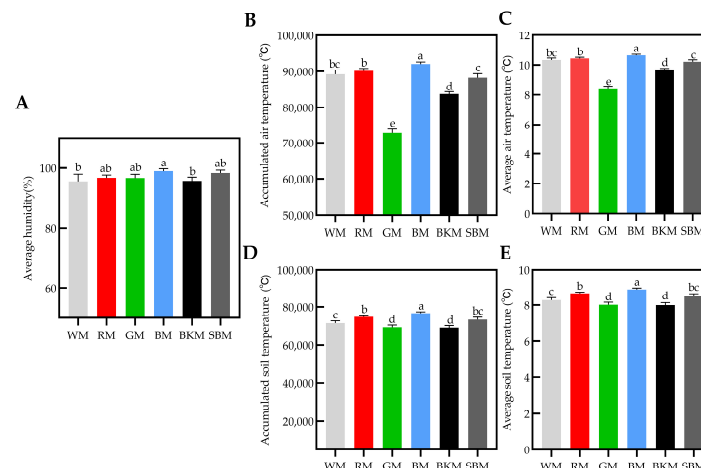


Figure 5. Effects of different colored films (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on (A) average humidity, (B) accumulated air temperature, (C) average air temperature, (D) accumulated soil temperature, (E) average soil temperature. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

3.2. Effects of Different Colored Films on the Number of *Morchella* Fruiting Bodies

The different colored film treatments affected the number of *Morchella* fruiting bodies (Figure 6). Under the BM treatment, the number of *M. septimelata* per square meter at the primordium, pinhead, and maturation stages was 5981, 4899, and 46, respectively, all significantly higher than those under the other treatments. The number of *M. sextelata* fruiting bodies tended to be similar to that of *M. septimelata*. Under the BM treatment,

the number of *M. sextelata* per square meter at the primordium, pinhead, and maturation stages was 5977, 4788, and 54, respectively, all significantly higher than those under the other treatments. The BM treatment induced the maximum number of fruiting bodies in *Morchella* across all developmental stages.

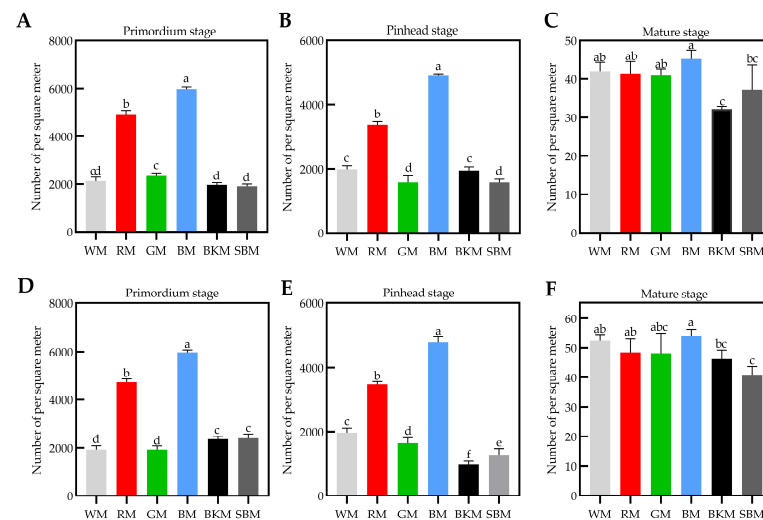


Figure 6. Effects of different colored films (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on the number of fruiting bodies of *M. septimelata* and *M. sextelata*. (A) Number of *M. septimelata* at the primordium stage per square meter; (B) Number of *M. septimelata* at the pinhead stage per square meter; (C) Number of *M. septimelata* at the mature stage per square meter; (D) Number of *M. sextelata* at the primordium stage per square meter; (E) Number of *M. sextelata* at the pinhead stage per square meter; (F) Number of *M. sextelata* at the mature stage per square meter. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

3.3. Effects of Different Colored Films on the Agronomic Traits and Yield of *Morchella*

Based on the data in Figure 7 and Table 1, the six colored film treatments affected the morphological characteristics of *M. septimelata* fruiting bodies. The BM treatment reached the maximum pileus length (82.97 mm), whereas the SBM treatment showed the minimum pileus length (68.40 mm). The pileus width under the BKM and SBM treatments was significantly smaller than that under the other treatments. The highest stipe length was recorded in the BM treatment (58.12 mm), while the lowest stipe length was recorded in the BKM (50.44 mm) and SBM (50.08 mm) treatments. Additionally, the BM treatment resulted in the greatest pileus-to-stipe ratio. In summary, the BM treatment resulted in the greatest pileus and stipe lengths, demonstrating its significant promoting effect on the agronomic traits of *M. septimelata*.



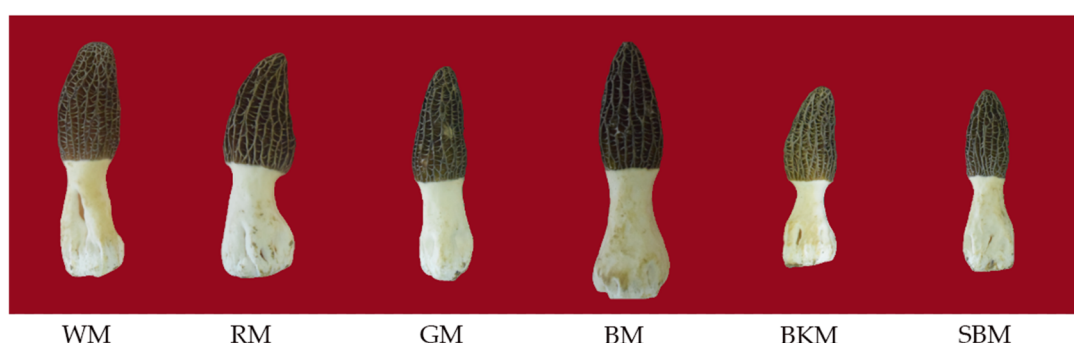
Figure 7. Effects of different colored films (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on the characteristics of the fruiting body of *M. septimelata*.

Table 1. Effects of different colored films on the characteristics of the fruiting body of *M. septimelata*.

Treatment	Pileus Length (mm)	Pileus Width (mm)	Stipe Length (mm)	Stipe Width (mm)	Pileus Length/Stipe Length
WM	75.97 ± 0.16 b	39.74 ± 0.17 a	54.23 ± 0.19 b	22.24 ± 1.17 a	1.40 ± 0.00 ab
RM	75.26 ± 0.16 b	40.01 ± 1.42 a	54.46 ± 0.53 b	22.57 ± 0.47 a	1.38 ± 0.01 b
GM	73.83 ± 0.83 c	39.00 ± 0.81 a	55.36 ± 0.74 b	21.27 ± 1.09 ab	1.33 ± 0.03 c
BM	82.97 ± 0.26 a	40.38 ± 1.03 a	58.12 ± 0.76 a	22.58 ± 1.56 a	1.43 ± 0.01 a
BKM	69.92 ± 0.24 d	31.38 ± 0.51 b	50.44 ± 0.37 c	19.83 ± 1.70 b	1.39 ± 0.01 b
SBM	68.40 ± 0.59 e	31.27 ± 0.77 b	50.08 ± 1.42 c	19.45 ± 0.19 b	1.37 ± 0.19 b

Note: white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM), silver-black film (SBM). All data are presented as mean ± standard deviation. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

According to the data in Figure 8 and Table 2, the six colored film treatments affected the morphological characteristics of *M. sextelata* fruiting bodies. The BM treatment reached the maximum pileus length (70.76 mm), whereas the SBM treatment showed the minimum pileus length (42.54 mm). The greatest pileus width (35.26 mm) occurred in the RM treatment, whereas the smallest pileus width (11.54 mm) occurred in the SBM treatment. The greatest stipe length (58.03 mm) was recorded in the BM treatment, and the shortest stipe length (40.87 mm) was recorded in the BKM treatment. The greatest stipe width was observed in the BM (35.14 mm) and RM (33.84 mm) treatments. Furthermore, similar to *M. septimelata*, the BM treatment resulted in the greatest pileus-to-stipe ratio, indicating that the BM treatment promoted pileus elongation.

**Figure 8.** Effects of different colored films (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on the characteristics of the fruiting body of *M. sextelata*.**Table 2.** Effects of different colored films on the characteristics of the fruiting body of *M. sextelata*.

Treatment	Pileus Length (mm)	Pileus Width (mm)	Stipe Length (mm)	Stipe Width (mm)	Pileus Length/Stipe Length
WM	60.91 ± 0.09 b	28.49 ± 2.32 b	51.48 ± 0.12 b	27.63 ± 2.36 b	1.18 ± 0.00 c
RM	61.64 ± 1.19 b	35.26 ± 0.52 a	51.78 ± 0.59 b	33.84 ± 1.23 a	1.19 ± 0.01 b
GM	54.92 ± 0.76 c	23.63 ± 1.51 c	45.86 ± 0.41 c	22.32 ± 0.25 c	1.20 ± 0.01 b
BM	70.76 ± 0.68 a	35.12 ± 0.59 a	58.03 ± 0.55 a	35.14 ± 2.94 a	1.22 ± 0.00 a
BKM	44.57 ± 0.55 d	15.12 ± 0.78 d	40.87 ± 0.43 e	17.29 ± 0.44 d	1.09 ± 0.00 d
SBM	42.54 ± 0.30 e	11.54 ± 0.41 e	41.85 ± 0.31 d	15.18 ± 0.88 d	1.02 ± 0.19 e

Note: white film (WM), red film (RM), green film (GM), blue film (BM), black film (BKM) silver-black film (SBM). All data are presented as mean ± standard deviation. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

Different colored film treatments resulted in differences in the weight of a single fruiting body and yield of *M. septimelata*. Compared with the WM treatment, the BM treatment resulted in the greatest weight of a single fruiting body of *M. septimelata* (37.07 g), representing an increase of 12.23%. Compared with the WM treatment, the SBM treatment

resulted in the lowest weight of a single fruiting body (25.73 g), representing a decrease of 22.10% (Figure 9A). In addition, compared with the WM treatment, the BM treatment resulted in the highest yield per square meter of *M. septimelata* (1.68 kg), representing an increase of 20.86%. Conversely, compared with the WM treatment, the BKM and SBM treatments resulted in the lowest yields, representing decreases of 34.53% and 32.37%, respectively (Figure 9B). Similarly, different colored film treatments also affected the weight of a single fruiting body and yield per square meter of *M. sextelata*. The weight of a single fruiting body of *M. sextelata* was greatest in the BM treatment (33.87 g), representing an increase of 18.14%. By contrast, the BKM (18.77 g) and SBM (18.70 g) treatments resulted in the lowest weight of a single fruiting body (Figure 9C). In addition, the yield of *M. sextelata* was greatest in the BM treatment (1.83 kg), representing an increase of 25.34%, whereas the lowest yield (0.76 kg) occurred in the SBM treatment (Figure 9D). Overall, the BM treatment significantly increased the weight of a single fruiting body and yield of *Morchella*.

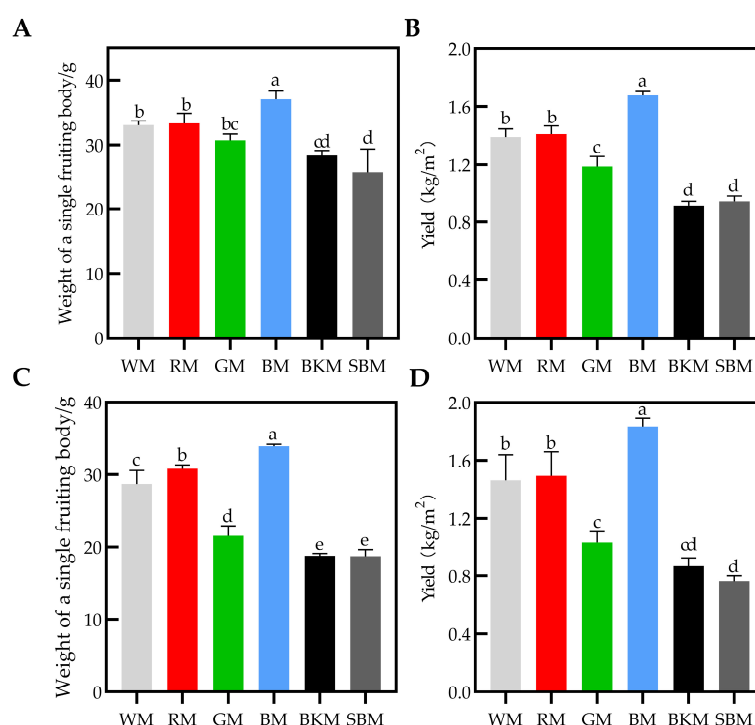


Figure 9. Effects of different colored film treatments (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on the weight of a single fruiting body and yield of *M. septimelata* and *M. sextelata*. (A) Weight of a single fruiting body of *M. septimelata*; (B) Yield of *M. septimelata*; (C) Weight of a single fruiting body of *M. sextelata*; (D) Yield of *M. sextelata*. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

3.4. Effects of Different Colored Films on the Crude Protein, Polysaccharide, and Fiber Contents of *Morchella*

Crude protein, crude polysaccharide, and crude fiber contents are important indicators of the nutritional quality of *Morchella* fruiting bodies. In this study, the different colored film treatments affected the nutritional quality of *M. septimelata* and *M. sextelata* (Figure 10). No significant differences in crude protein content were detected among the RM, GM, BKM, and SBM treatments for *M. septimelata*. The crude polysaccharide content of *M. septimelata* was the highest in the RM treatment (12.84 g/100 g), representing an increase of 47.42% compared with that in the WM treatment. The crude fiber content was the highest in the BM treatment (23.49 g/100 g), representing an increase of 16.92% compared with that in the WM treatment. No significant differences in crude protein content were detected among

the WM, RM, BKM, and SBM treatments for *M. sextelata*. The crude polysaccharide content of *M. sextelata* was the highest in the RM treatment (11.76 g/100 g), representing an increase of 44.12% compared with that in the WM treatment. The BM treatment also increased the crude fiber content of *M. sextelata*, representing an increase of 2.63% compared with that in the WM treatment. The RM treatment was most effective at increasing crude polysaccharide content, whereas the BM treatment performed best at increasing crude fiber content.

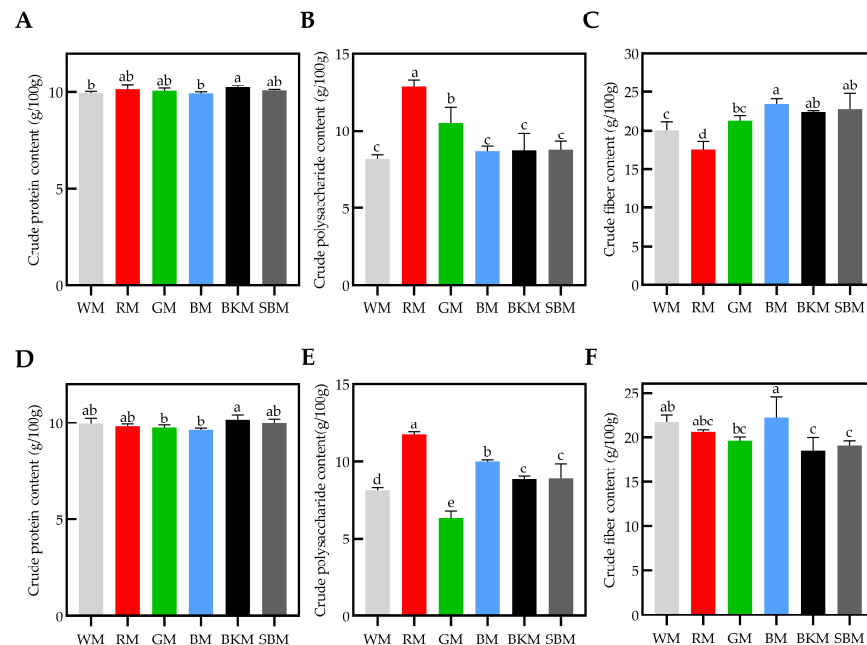


Figure 10. Effects of different color film treatments (WM: white film; RM: red film; GM: green film; BM: blue film; BKM: black film; SBM: silver-black film) on the crude protein, polysaccharide, and fiber contents of *M. sextelata* and *M. septimelata*. (A) Crude protein content of *M. septimelata*; (B) Crude polysaccharide content of *M. septimelata*; (C) Crude fiber content of *M. septimelata*; (D) Crude protein content of *M. sextelata*; (E) Crude polysaccharide content of *M. sextelata*; (F) Crude fiber content of *M. sextelata*. Values labeled with different letters in the graph are significantly different based on the least significant difference (LSD) multiple range test ($p < 0.05$).

3.5. Correlation Analysis of Different Colored Films on the Microenvironment and Development of *M. septimelata* and *M. sextelata*

To gain insight into the relationships between the different colored film treatments of *M. septimelata* and *M. sextelata* and the development indicators of morels, a correlation analysis was performed. The results (Figure 11) indicated that in *M. septimelata*, light intensities at various time points were positively correlated with most development indicators. Among them, light intensities at 9:30 and 16:30 were significantly positively correlated with the number of maturation stages per square meter, pileus length, pileus width, stipe length, stipe width, weight of a single fruiting body, and yield. The number of maturation stages per square meter was significantly positively correlated with pileus length and width, stipe length and width, and yield. Crude protein content was significantly negatively correlated with the number of maturation stages per square meter. In *M. sextelata*, light intensity at 16:30 was significantly positively correlated with pileus length, pileus width, stipe length, stipe width, weight of a single fruiting body, and yield. Moreover, crude fiber content was significantly and positively correlated with pileus length and width, stipe length and width, weight of a single fruiting body, and yield. In summary, light intensity was positively correlated with agronomic traits and yield in both species.

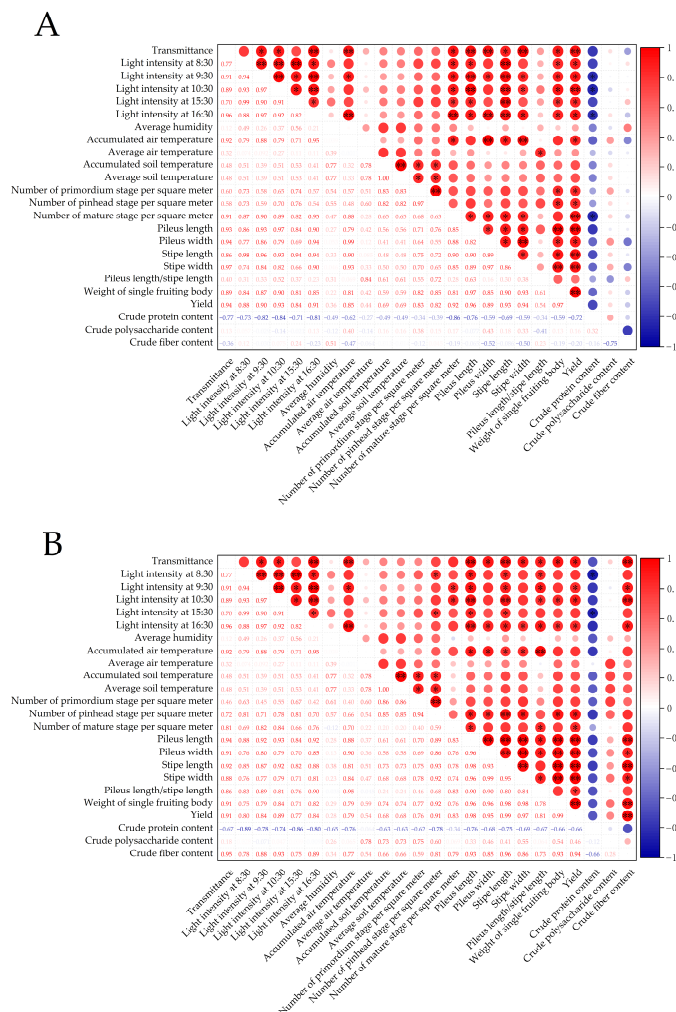


Figure 11. Correlation analysis between the *Morchella* microenvironment and development indicators of different colored film treatments. (A) *M. septimelata*; (B) *M. sextelata*. * $p \leq 0.05$, ** $p \leq 0.01$.

4. Discussion

Colored films are pivotal regulatory factors in *Morchella* cultivation, and they significantly impact environmental factors, including transmittance, light intensity, and temperature. Blue films exhibit higher transmittance, whereas black mulch films exhibit lower transmittance [35]. In this study, the transmittance of 92% at 405 nm was highest under the BM treatment. However, the transmittance was maintained at a relatively low level across all wavelengths under the BKM and SBM treatments. Black and silver-black films are known to result in low light intensity inside and outside the mulch [30]. Consistent with these findings, the light intensity under the BM treatment was significantly greater than that under the other treatments at all sampling time points, whereas the black and silver-black films maintained light intensity at low levels. In this study, compared with those in the other colored film treatments, the accumulated air temperature, accumulated soil temperature, average air temperature and average soil temperature in the BM treatment were significantly greater, whereas all the temperature indicators in the BKM and SBM treatments remained consistently low. Correlation analysis revealed that light intensity at 9:30 and 16:30 was significantly positively correlated with yield-related traits and agronomic characteristics in *Morchella*. However, Li [30] reported that a higher accumulated air temperature was observed under green film treatment, and these findings may be associated with the film thickness and application method.

Different colored films affect the number, morphology, weight of a single fruiting body, and yield of *Morchella*. Among all the treatments, the BM treatment had the most obvious promoting effect on *Morchella*. Under the BM treatment, blue light was the dominant light quality. In ascomycetes and basidiomycetes, blue light is primarily perceived by the photoreceptors WC-1 and WC-2, which activate downstream transcriptional cascades that regulate morphogenesis, secondary metabolism, and oxidative stress responses [36,37]. In *C. militaris*, the blue light receptor gene *Cmwc-1* is inactivated via homologous recombination. The strains with this inactivated gene exhibited markedly thicker aerial hyphae, disordered fruiting body development, a significant reduction in conidial formation, and decreased production of carotenoids and cordycepin [38]. Mixed irradiation with far-red light and blue light significantly increased the fresh weight of *Lyophyllum decastes* fruiting bodies, decreased the number of fruiting bodies and promoted pileus pigmentation [39]. Far-red light treatment increased the number of primordia during the development of *Pleurotus citrinopileatus*, and blue light treatment increased the color uniformity and yield of the pileus [40]. Similar promoting effects of blue light on fruiting body development have been observed in *Pleurotus ostreatus* [41], and *Hericium coralloides* [42]. In this study, the BM treatment resulted in the greatest number of primordia and pinhead and mature-stage fruiting bodies in *M. septimelata* and *M. sextelata*. This treatment also promoted pileus elongation and increased the weight of the fruiting body and yield. By contrast, the BKM and SBM treatments resulted in fewer fruiting bodies and lower yields of *Morchella*. This may be due to the low light transmittance of these two films. A nearly dark environment is formed under the films and hinders the normal development of *Morchella*, which is consistent with the findings of Li [30]. Silver-black film and black film treatments cause ascomata malformation in *M. importuna*, and these ascomata fail to mature normally.

Nutritional quality is a core indicator for evaluating the edibility of *Morchella* fruiting bodies. Different light qualities produced by different colored films further regulate the accumulation of nutritional components [43]. The mechanism by which light quality regulates nutritional quality is closely related to the differential regulation of primary and secondary metabolism by fungal light signaling pathways. Integrated transcriptomic and metabolomic analyses in *Flammulina filiformis* revealed that blue light promoted lysine and carbohydrate synthesis, whereas red light upregulated the expression of glycosyltransferase genes involved in polysaccharide biosynthesis [44]. Red light increased the water-soluble polysaccharide content in *Pleurotus eryngii*, whereas white light promoted protein accumulation [45]. Similarly, other studies have shown that blue light or combined light treatments increase crude protein and polysaccharide contents in *Lyophyllum decastes* [39], red light increases crude fiber content in *Tremella fuciformis*, blue light promotes crude polysaccharide content [46], red light increases crude polysaccharide content in *Pleurotus ostreatus*, and yellow light increases crude protein content [47]. Blue light irradiation optimizes the nutritional and flavor qualities of *P. citrinopileatus*, increasing the proportions of umami and sweet amino acids and increasing the odor activity values (OAVs) of key aroma compounds [48]. In this experiment, the crude polysaccharide content increased under the RM treatment, whereas the crude fiber content increased under the BM treatment, indicating that the RM can promote the accumulation of crude polysaccharides in *Morchella* and that the BM can facilitate the accumulation of crude fiber. Correlation analysis further revealed that the crude fiber content of *M. sextelata* was positively correlated with agronomic traits and yield, whereas the crude protein content of *M. septimelata* was negatively correlated with yield-related parameters. However, this study evaluated only crude protein, crude polysaccharide, and crude fiber contents. A more comprehensive assessment of nutritional quality, including detailed analyses of amino acid profiles, bioactive compounds, and

other functional components, is needed to fully elucidate the effects of colored films on *Morchella* quality.

Our research on the systematic analysis of the colored film-mediated regulation of the cultivation microenvironment and fruiting body development in *M. septimelata* and *M. sextelata* provides a theoretical foundation for the optimization of microenvironment regulation and cultivation technology in the protected cultivation of *Morchella*. The results of this study revealed that BM can synergistically promote morphological development, yield improvement and crude fiber accumulation in *Morchella* by optimizing the light quality composition and increasing the light intensity and the accumulated temperature effect. This discovery provides technical evidence for the precise regulation of the cultivation microenvironment in the protected production of *Morchella*. The colored film regulation patterns associated with the microenvironment and development of *Morchella* observed in this study may serve as a technical reference for its protected cultivation. However, further validation across multiple locations and seasons is needed. Future work may also explore the transition from cultivation environment regulation to light quality-mediated metabolic regulation and quality improvement, particularly through more detailed compositional analyses.

5. Conclusions

These findings indicate that different colored films significantly influence the microenvironment and development of *M. septimelata* and *M. sextelata*. BM treatment improved the light environment and increased the number of fruiting bodies, the pileus length, the weight of a single fruiting body and yield, and the crude fiber content under the conditions of this study. BM has application potential for the protected cultivation of *Morchella* within the scope of this study, but its broader applicability requires further validation through trials across additional sites and seasons.

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