Data-Driven Optimization of Moss Growth Under Variable Light Conditions: A Computational Framework for Ecological Restoration

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ABSTRACT This study presents a data-driven computational framework for optimizing moss cultivation under variable light environments to support ecological restoration and intelligent environmental management applications. Three moss species (Didymodon tectorum, Abietinella abietina, and Racomitrium canescens) were cultivated under five light spectra (red, blue, green, yellow, and white) and three photoperiod regimes (8 h, 16 h, and 24 h). A standardized experimental dataset comprising 45 treatment combinations was established to evaluate growth characteristics, photosynthetic pigment accumulation, and antioxidant defense responses. Results demonstrated that red light under a 24 h photoperiod produced the highest biomass performance, with Didymodon tectorum achieving a height of 5.45 mm and coverage of 85%. Blue light significantly enhanced photosynthetic activity, yielding a maximum chlorophyll A content of 0.228 mg g^{-1} FW and promoting proline accumulation associated with stress tolerance. Green light under an 8 h photoperiod generated the strongest antioxidant response, with superoxide dismutase activity reaching 28.817 $U{\cdot}mg^{-1}$. Based on the experimental dataset, a computational decision framework and light optimization algorithm were developed to identify optimal spectral–temporal combinations for growth enhancement and stress-resistance management. The proposed framework is compatible with LED-based spectral regulation systems, optical sensing networks, wireless environmental monitoring platforms, and intelligent ecological restoration infrastructures. By integrating biological response modeling with data-driven decision strategies, this work provides an engineering-oriented methodology for adaptive light control and smart cultivation systems in ecological restoration and sustainable environmental applications.

INDEX TERMS moss cultivation, spectral optimization, intelligent sensing systems, ecological restoration

I. INTRODUCTION

MOSS plants are among the oldest plants on Earth and are widely distributed across various ecosystems. As pioneer plants in natural succession, mosses play a crucial ecological role in preserving biodiversity, maintaining soil moisture, and purifying the air [1]. With the intensification of ecological and environmental issues, the application of moss plants in ecological restoration has garnered increasing attention. This is especially due to mosses' significant potential in addressing critical environmental problems such as heavy metal pollution, soil erosion, and desertification—issues often exacerbated by or critical to large- scale industrial activities[2].

Plant growth and development are influenced by various environmental factors, with light quality and photoperiod being key factors. Light quality refers to the composition of light wavelengths. Different wavelengths of light affect various physiological processes in plants, such as photosynthesis, hormone levels, and antioxidant capacity, through distinct mechanisms [3]. Existing studies show that the influence of light quality on plant growth is not only reflected in growth rate and photosynthesis efficiency but also profoundly impacts the plant's metabolic pathways and ability to respond to stress [4]. The effects of light quality have become a hot topic in the field of plant physiology. Red light (620-750 nm) is commonly regarded as one of the most important light qualities for promoting plant growth. It primarily regulates plant growth and development through photoreceptors, such as phytochrome, a light-sensitive pigment [5]. Red light effectively enhances photosynthesis and promotes the synthesis of photosynthetic pigments, particularly in the growth of plant stems, leaves, and roots, showing significant promoting effects [6]. Red light also regulates plant growth morphology, promoting branching and root growth, thereby increasing plant biomass and productivity [7]. Similarly, blue light (450-495 nm) has also attracted significant attention regarding its impact on plant growth. Blue light affects plant photosynthesis and growth through blue light photoreceptors, such as cryptochrome and phototropin [8]. It not only enhances the photosynthetic efficiency of plant leaves but also regulates the plant's antioxidant system, improving its resistance to environmental stresses. Research has shown that blue light helps increase chlorophyll content and photosynthetic efficiency, significantly enhancing plant growth rate and stress resistance, particularly under limited water and nutrient conditions. Blue light can effectively improve plants' drought, cold, and stress resistance [9,10]. Research on green light (500-570 nm) is relatively scarce, but in recent years, there has been increasing attention on its effects on plant growth. Green light has strong penetration ability, and its role in plant growth is complex and diverse [11]. Studies have shown that green light can regulate the plant's antioxidant system, enhancing its adaptability to oxidative stress [12]. Under strong light conditions, green light helps improve the plant's water use efficiency and aids in coping with adverse environments such as high temperatures and drought by increasing leaf thickness and reducing transpiration [13]. In addition to light quality, photoperiod is also an important factor influencing plant growth. Different photoperiods directly affect the plant's growth cycle, photosynthetic efficiency, and stress resistance [7]. Existing research indicates that plant responses to different photoperiods typically depend on light quality and plant species. Short photoperiods (usually less than 8 hours) may limit the accumulation of photosynthetic products, but they can activate the plant's stress responses, enhancing stress tolerance. This is particularly important for moss plants, as they typically grow in low-light environments [14]. Longer photoperiods extend the plant's photosynthesis duration, promote the accumulation of photosynthetic products, and enhance its growth ability. However, a prolonged photoperiod, such as the 24-hour continuous light treatment, may lead to photoinhibition, particularly when light intensity is too high, which can suppress normal plant growth [15].

Although extensive research has been conducted on the effects of light quality and photoperiod on plant growth, studies specifically focused on moss plants remain relatively scarce. While most existing studies focus on economic crops or model plants, there is limited comprehensive research on the growth, photosynthesis, and antioxidant responses of moss plants under different light qualities and photoperiods. This gap is particularly notable considering the growing interest in utilizing mosses as a sustainable source for bio-based materials or ecological solutions within the industry [9]. Recent advances in computational approaches have opened new possibilities for optimizing plant growth conditions through data-driven modeling. The structured experimental design in this study (5 light qualities $\times$ 3 photoperiods $\times$ 10 physiological parameters) not only addresses fundamental questions in moss physiology but also generates a dataset amenable to machine learning applications. This dual perspective bridges traditional botanical research with emerging computational tools for ecological management. Based on this, this study systematically investigates the effects of different light qualities (red, blue, green, yellow, white) and photoperiods (8h, 16h, 24h) on three moss species (Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum), generating a comprehensive dataset of 45 treatment combinations (5 light qualities $\times$ 3 photoperiods $\times$ 3 species) with standardized growth, photosynthetic pigment, and antioxidant activity measurements. The experimental design enables both mechanistic analysis of light regulation on moss physiology [14] and subsequent computational applications for ecological restoration. Current challenges in moss restoration, including slow growth rates and propagation limitations [9], may be addressed through light regime optimization, as demonstrated by the structured dataset's potential to inform artificial propagation protocols and field-scale implementation [10].

II. MATERIALS AND METHODS

A. EXPERIMENTAL MATERIALS

1) Collection of Moss Samples

In this experiment, three moss species were selected as the experimental materials: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum. These species were collected from Qing Shuihe County, Hohhot City, Inner Mongolia (Longitude 111.64725853, Latitude 39.98295126) and Daqingshan (Longitude 112.0237202, Latitude 41.0236159). These species are characterized by good tolerance and large biomass. Well-developed moss samples with approximately 1 cm of soil were selected as inoculation materials, including Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum. The original soil from the sample collection area was used as the culture substrate. To avoid the influence of other ground vegetation and litter, the surface soil was removed, and soil from 5-20 cm depth was collected. The soil was placed in a shaded area to air dry, then ground and sieved through a 0.150 mm mesh for later use.

2) Processing of Moss Samples

Indoor cultivation was used. The moss samples were first washed to remove surface soil until no visible impurities remained. The aerial parts of the three moss species were disinfected with 75% ethanol for 60 seconds. The sterilized moss was then cut into small pieces and spread on the culture substrate, with 0.5 g of material placed in each plastic cup. After sealing with plastic wrap, the samples were placed in an artificial climate chamber at the College of Grassland Science for cultivation. A total of 45 treatments were set up (5 light colors $\times$ 3 light durations $\times$ 3 moss species), with 5 repetitions for each treatment. During the light experiment phase, the samples were exposed to red, yellow, blue, white, and green light sources under conditions of 8, 16, and 24-hour photoperiods. The light intensity for all treatments was rigorously standardized to a Photosynthetic Photon Flux Density (PPFD) of 80 μmol$\cdot$m$^{-2}\cdot$s^{-1} at the moss surface, measured using a quantum sensor (Model, Manufacturer). This PPFD-based standardization ensures that the photosynthetic photon availability, which is the physiologically relevant metric, is equivalent across all tested light qualities (red, blue, green, yellow, and white light), thereby eliminating the confounding variable of energy quantity and allowing for a valid comparison of spectral effects on moss growth and physiology. While the illuminance measured in Lux may have varied due to the different spectral composition of the light sources, Lux is not a physiologically relevant metric for photosynthesis. Controlling by the universally accepted PPFD ensures methodological rigor and a valid comparison of the light quality effects. The room temperature was 24°C, and the humidity was 45%.

B. MEASUREMENT OF INDICATORS

The cultured samples were rinsed three times with distilled water to remove visible sand and debris, then dried to remove surface moisture. The required sample weights for different indicators were measured. Chlorophyll content (Chl) was measured using a 95% anhydrous ethanol extraction method, with 95% ethanol as the blank. Absorbance was measured at 665 nm, 649 nm, and 470 nm. Carotenoid content was measured using UV-Vis spectrophotometry. Soluble sugar content (SS) was measured using the anthrone colorimetric method. Malondialdehyde (MDA) content in each treatment/control was determined using the thiobarbituric acid (TBA) colorimetric method. The absorbance difference was measured at 532 and 600 nm using spectrophotometry. Proline content was measured using the acidic ninhydrin colorimetric method. Superoxide dismutase (SOD) activity was measured using the NBT photochemical reduction method, with a 50% inhibition of nitroblue tetrazolium chloride (NBT) photoreduction defined as 1 enzyme activity unit (U). Peroxidase (POD) activity was measured using the guaiacol method.

C. DATA PROCESSING

A one-way ANOVA was performed using SPSS 26.0 software to analyze the differences in moss-related physiological indicators under different light qualities with the same photoperiod and the differences under the same light quality with different photoperiods. Data are presented as means $\pm$ standard error (Means $\pm$ SE). All graphs were created using Origin 2023b software.

III. RESULTS AND ANALYSIS

A. ANALYSIS OF GROWTH INDICATORS

Growth indicators (height, coverage, and density) are important parameters for evaluating the growth status of moss plants. The experimental results show that light quality and photoperiod have a significant impact on the growth of moss plants (including height, coverage, and density). The red light treatment showed the strongest effect in promoting moss growth, especially under the 24-hour red light condition, where the height, coverage, and density of Didymodon tectorum reached their optimal levels. Under 24 hours of red light, the height of Didymodon tectorum was 5.45 mm, coverage was 85%, and density was 135 plants/cm^2, significantly higher than that of other light treatments. This indicates that red light can significantly promote moss growth, especially under longer photoperiods. Similar growth-promoting trends were observed across the other two species: for Abietinella abietina and Rhytidium rugosum, the maximum height and coverage also occurred under the 24-hour red light condition. Blue light also effectively promotes moss growth, especially under the 24-hour blue light condition, where the height of Didymodon tectorum was 3.18 mm, coverage was 55%, and density was 120 plants/cm^2. The effect of blue light was second only to that of red light, showing its adaptability in promoting moss growth. In contrast, green light and yellow light had weaker effects on moss growth. Particularly under short photoperiods (e.g., 8 hours), the effect of green light on the height of Didymodon tectorum was only 2.44 mm, coverage was 40%, and density was 58 plants/cm^2. The yellow light treatment had a more significant inhibitory effect on growth, especially under the 8-hour yellow light condition, where the height of Didymodon tectorum was 2.12 mm, coverage was 55%, and density was 76 plants/cm^2. Although extending the photoperiod could improve the growth indicators of moss, the effects of yellow and green light were consistently weaker, particularly under short photoperiods. These two light qualities had some inhibitory effects on the growth of moss plants. The growth responses across all three species consistently showed the highest promotion under red light (24h) and the weakest or inhibitory effects under yellow and green light, especially at the 8h photoperiod.

B. CHANGES IN PHOTOSYNTHETIC PIGMENT CONTENT

1) Changes in Chlorophyll A and Chlorophyll B

Chlorophyll A is one of the most important photosynthetic pigments, and its content reflects the strength of the plant's photosynthetic capacity, indirectly indicating the plant's growth vitality. Experimental data show that blue light and red light significantly increased the chlorophyll A content of moss plants, especially under the 24-hour blue light condition, where the chlorophyll A content of Didymodon tectorum was 0.228 mg/g FW, significantly higher than other treatments (such as green light and yellow light). This result indicates that blue light can effectively promote the photosynthesis of moss plants and enhance the plant's light energy utilization efficiency. This pattern was consistent, with blue light (24h) yielding the highest Chlorophyll A content for Abietinella abietina (approx. 0.25 mg$\cdot$g^{-1} FW) and Rhytidium rugosum (approx. 0.22 mg$\cdot$g^{-1} FW) as well.

In contrast, the yellow light treatment had a weaker effect on promoting chlorophyll A synthesis, especially under short photoperiods, where the chlorophyll A content was lower (Figure 1).

Chlorophyll B is another important photosynthetic pigment that assists chlorophyll A in absorbing light energy. Its content also reflects the photosynthetic efficiency and growth status of moss plants. Under the 24-hour red light condition, the chlorophyll B content of Didymodon tectorum was 0.425 mg/g FW, significantly higher than other light treatments. Blue light and white light treatments also significantly increased chlorophyll B content, especially under the 24-hour photoperiod, where the chlorophyll B content under blue light was 0.372 mg/g FW. For Abietinella abietina and Rhytidium rugosum, red light (24h) also led to the highest Chlorophyll B content (approx. 0.45 and 0.47 $mg{\cdot}g^{-1}$ FW, respectively), confirming the general positive impact of red light on this pigment across all species. Green light and yellow light had weaker effects on chlorophyll B synthesis, especially under short photoperiods, where the synthesis of chlorophyll B was poor, indicating that these light qualities have limited ability to promote moss photosynthesis (Figure 2).

C. CHANGES IN CAROTENOID CONTENT

Carotenoids are important accessory pigments in photosynthesis, playing a key role in light energy absorption and antioxidant protection. Carotenoids play an important role in the photosynthesis and antioxidant responses of moss plants. According to the experimental results, blue light and red light significantly increased the carotenoid content in moss plants. Particularly under the 24-hour blue light treatment, the carotenoid content of Didymodon tectorum was 0.319 mg/g FW, significantly higher than that of other light quality treatments. Consistent with this, Abietinella abietina and Rhytidium rugosum also exhibited maximal carotenoid content under blue light (24h) (approx. 0.30 and 0.29 $mg{\cdot}g^{-1}$ FW, respectively). The effects of green light and yellow light treatments on carotenoid promotion were weaker, especially under short photoperiods, where the carotenoid content under yellow light was significantly lower than that of other light quality treatments (Figure 3).

D. CHANGES IN ANTIOXIDANT SYSTEM ACTIVITY

1) Changes in Superoxide Dismutase (SOD) Activity

SOD is one of the most important enzymes in the antioxidant system, capable of scavenging superoxide radicals and protecting plants from oxidative damage. Experimental data show that green light significantly increased SOD activity under short photoperiods (8 hours), especially under the 8-hour green light treatment for Didymodon tectorum, where SOD activity reached 28.817 $U{\cdot}mg^{-1}$, significantly higher than that of other light quality treatments. This indicates that green light can effectively enhance the antioxidant capacity of moss in a short period of time. This pattern was highly consistent across all species, with the 8-hour green light treatment resulting in the highest SOD activity for Abietinella abietina (approx. 29 $U{\cdot}mg^{-1}$) and Rhytidium rugosum (approx. 29 $U{\cdot}mg^{-1}$), underscoring the universal short-term antioxidant benefit of green light. In contrast, under the 24-hour photoperiod, the SOD activity under yellow light was relatively low, at only 14.304 $U{\cdot}mg^{-1}$, suggesting that yellow light has a minimal effect on the antioxidant capacity of moss (Figure 4).

2) Changes in Peroxidase (POD) Activity

Peroxidase is another key enzyme in the antioxidant system, capable of scavenging reactive oxygen species such as hydrogen peroxide. The experimental results show that red light significantly increased POD activity under short photoperiod conditions (8 hours), especially under the 8-hour red light treatment for Didymodon tectorum, where POD activity was 0.330 $U{\cdot}mg^{-1}$, significantly higher than that of other light quality treatments. This maximum induction of POD activity by red light (8h) was also observed for Abietinella abietina (approx. 0.28 $U{\cdot}mg^{-1}$) and Rhytidium rugosum (approx. 0.34 $U{\cdot}mg^{-1}$), highlighting a species-general role for short-period red light in enhancing this specific antioxidant enzyme. In contrast, the effects of green light and yellow light on POD activity were weaker, particularly under longer photoperiod conditions, where POD activity was lower, indicating that these light qualities had a smaller impact on the antioxidant capacity of moss (Figure 5).

3) Changes in Proline and Malondialdehyde (MDA) Content

Proline is an important osmotic regulator, playing a key role in protecting cells, stabilizing enzyme activity, and regulating osmotic pressure under stress conditions such as drought and salinity. The experimental results show that blue light and red light were particularly effective in promoting proline accumulation. Especially under the 24-hour blue light treatment, the proline content of Didymodon tectorum was 41.23 μg/g FW, significantly higher than that of other light quality treatments. The proline content under red light was the second highest, reaching 33.48 μg/g FW. The trend of blue light (24h) resulting in the highest proline content was consistently observed across all three species (Abietinella abietina: approx. 45 μg/g FW; Rhytidium rugosum: approx. 45 μg/g FW), confirming its optimal effect on osmotic regulation. In contrast, yellow light and green light treatments under short photoperiods (e.g., 8 hours) resulted in lower proline content, indicating that they had a weaker effect on enhancing the stress resistance of moss plants (Figure 6).

Malondialdehyde (MDA) is a product of lipid peroxidation in plant membranes, and its content directly reflects the extent of membrane damage under oxidative stress conditions. The experiment showed that red light and green light significantly increased the MDA content in moss under the 16-hour photoperiod, particularly under the 16-hour red light treatment, where the MDA content of Didymodon

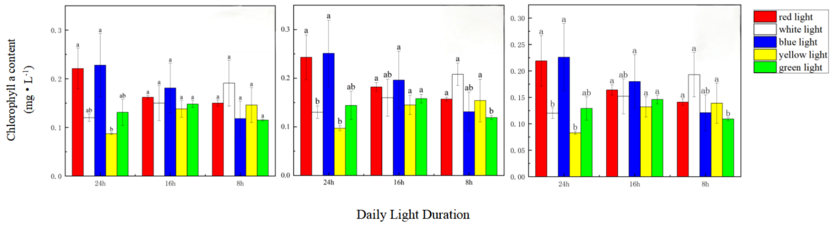

FIGURE 1. The effect of different light qualities and light durations on chlorophyll a content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

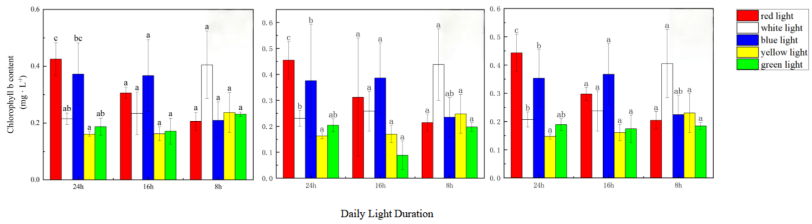

FIGURE 2. The effect of different light qualities and light durations on chlorophyll b content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

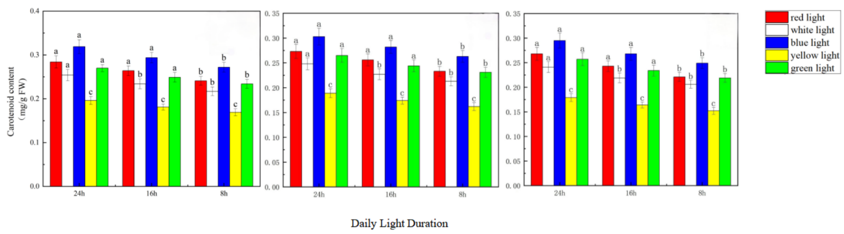

FIGURE 3. The effect of different light qualities and light durations on carotenoid content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

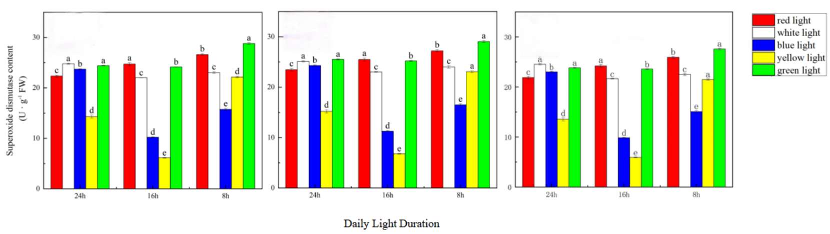

FIGURE 4. The effect of different light qualities and light durations on SOD activity in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

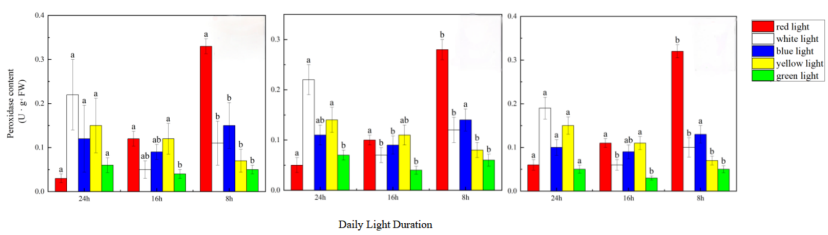

FIGURE 5. The effect of different light qualities and light durations on POD activity in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

tectorum was 4.527 U·mg^{-1}, significantly higher than that of other light quality treatments. This peak MDA content under 16-hour red light was also evident in Abietinella abietina (approx. 4.2 μmol·g^{-1} FW) and Rhytidium rugosum (approx. 4.5 μmol·g^{-1} FW), suggesting this regime may cause a temporary increase in oxidative stress. In

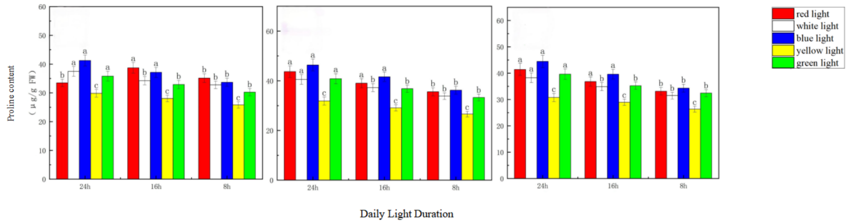

FIGURE 6. The effect of different light qualities and light durations on proline content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

contrast, blue light and white light treatments under the 24-hour photoperiod resulted in lower MDA content, indicating stronger protective effects on the moss plant cell membranes (Figure 7).

E. CHANGES IN SOLUBLE SUGAR CONTENT

Soluble sugars are important osmotic regulators in plants under stress conditions such as drought and salinity, and they also play a key role in energy storage and metabolism. The experimental results show that red light significantly promoted the accumulation of soluble sugars in moss plants under short photoperiods (e.g., 8 hours). Especially under the 8-hour red light treatment for Didymodon tectorum, the soluble sugar content reached 15.147 U$\cdot$mg^{-1}, significantly higher than that of other light quality treatments. Red light (8h) also induced the highest soluble sugar content for Abietinella abietina (approx. 15 mg$\cdot$g^{-1}) and Rhytidium rugosum (approx. 14.5 mg$\cdot$g^{-1}), establishing this as the optimal condition for soluble sugar accumulation across the species. Blue light and white light also showed significant promoting effects under the 16-hour photoperiod, with soluble sugar contents of 14.412 U$\cdot$mg^{-1} and 13.431 U$\cdot$mg^{-1}, respectively, indicating that these light qualities can enhance the osmotic regulation capacity and stress resistance of moss. In contrast, the effects of yellow light and green light on soluble sugar accumulation were relatively weak, especially under short photoperiods (8 hours), where the soluble sugar contents were 7.502 U$\cdot$mg^{-1} and 8.891 U$\cdot$mg^{-1}, respectively, indicating their weaker role in enhancing the osmotic regulation capacity of moss plants (Figure 8).

F. COMPUTATIONAL DECISION FRAMEWORK

Algorithm 1. Light Optimization Lookup Algorithm
Input:
`Light_quality` ∈ {Red, Blue, Green, Yellow, White}
`Photoperiod` ∈ {8h, 16h, 24h}
`Target` ∈ {Max_Growth, Max_Stress_Resistance}
Procedure:
1. Load `experimental_dataset`:
`Growth_metrics` (height, coverage, density)
`Photosynthetic_pigments` (Chl A, Chl B, Carotenoids)
`Antioxidant_activity` (SOD, POD, Proline, MDA)
2. Switch `Target`:
Case `Max_Growth`:
`optimal_setting` ← SELECT `Light_quality`, `Photoperiod`
FROM dataset
WHERE height + coverage = MAX(height + coverage)
Case `Max_Stress_Resistance`:
`optimal_setting` ← SELECT `Light_quality`, `Photoperiod`
FROM dataset
WHERE (SOD + POD + Proline) - MDA = MAX((SOD + POD + Proline) - MDA)
3. Output `optimal_setting`
End

This pseudocode demonstrates how our experimental data can structure a rule-based decision system. For example: To maximize growth (Target = Max_Growth), the algorithm selects Red light (24h) based on our experimental results (Section Analysis of Growth Indicators). To enhance stress resistance (Target = Max_Stress_Resistance), Blue light (16h) would be prioritized. Future implementations could integrate real-time sensor data with this lookup logic for adaptive control.

IV. DISCUSSION

This study systematically analyzed the effects of different light qualities and photoperiods on the growth, photosynthetic pigment content, and antioxidant system activity of three moss species, revealing the significant regulatory effects of different light environments on the physiological characteristics of moss plants. The results indicate that red light, blue light, and green light play different roles in regulating moss growth, photosynthetic capacity, and stress resistance, providing important theoretical support for the artificial cultivation and propagation of moss plants.

Firstly, red light significantly promoted moss growth under a 24-hour daily light condition, with the height, coverage, and density of Didymodon tectorum reaching optimal levels. The promotion of moss growth by red light may be related to its regulatory effects on cell division and elongation. Studies have shown that red light can promote plant cell proliferation and elongation by regulating the synthesis and signaling of plant hormones, such as auxins and gibberellins [16,17]. In addition, red light significantly increased peroxidase (POD) activity and soluble sugar content under short photoperiods, indicating its important role in enhancing the moss's antioxidant capacity and osmotic regulation ability. POD is a key enzyme in the plant antioxidant system, responsible for scavenging reactive oxygen species such as hydrogen peroxide (H_2O_2)

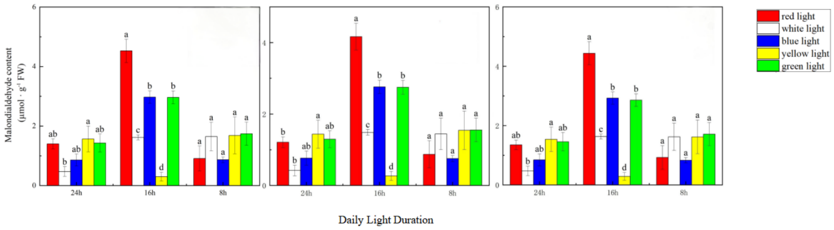

FIGURE 7. The effect of different light qualities and light durations on MDA content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

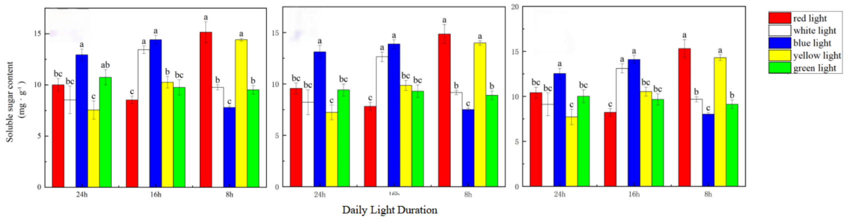

FIGURE 8. The effect of different light qualities and light durations on soluble sugar content in three moss species (from left to right: Didymodon tectorum, Abietinella abietina, and Rhytidium rugosum)

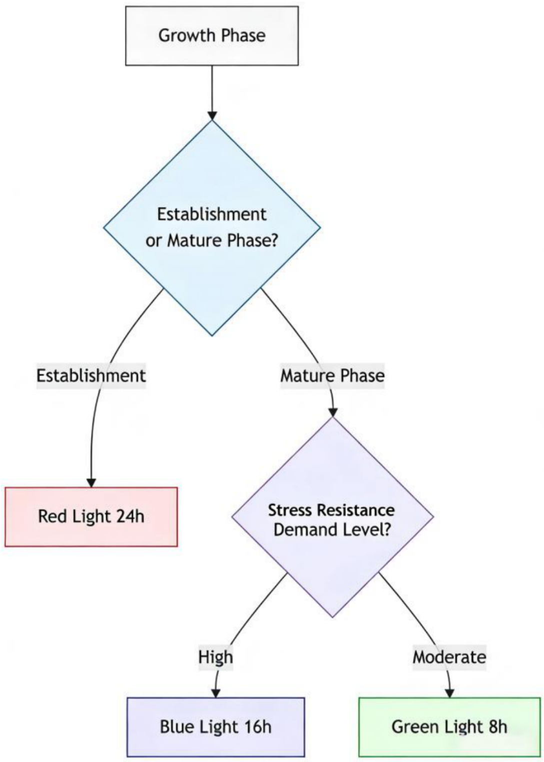

FIGURE 9. The example of decision workflow for light quality optimization in moss cultivation (Diamond: growth phase selection; Red rectangle: establishment phase recommendation; Blue/Green rectangles: mature phase options based on stress resistance demand; Arrow pathways: decision logic derived from experimental results.)

to protect cells from oxidative damage [18]. However, it is crucial to address the finding that red light (16h) and green light (16h) significantly increased Malondialdehyde (MDA) content (e.g., Didymodon tectorum MDA: 4.527 $U{\cdot}mg^{-1}$ under 16h red light), which indicates an elevated level of lipid peroxidation and cellular membrane damage. This elevated MDA under an intermediate photoperiod, despite the general growth-promoting effect of red light, suggests a potential trade-off or temporary stress imbalance. A possible explanation is that the 16-hour red light regime may drive high photosynthetic activity, leading to an overproduction of reactive oxygen species (ROS) during the extended light exposure, which temporarily overwhelms the moss's enzymatic antioxidant defenses (like SOD and POD) that are better induced under 8-hour photoperiods. Conversely, the lower MDA content observed under 24-hour blue and white light conditions indicates that these long photoperiods, especially with blue light, trigger superior protective mechanisms to maintain membrane integrity, confirming their long-term stress-mitigating benefits. By increasing POD activity, red light enhances the moss's tolerance to oxidative stress, providing theoretical support for its application in environmental pollution remediation. Secondly, blue light significantly increased the photosynthetic pigment content of moss, especially chlorophyll A and carotenoids, indicating its potential in enhancing photosynthetic capacity. Existing studies suggest that blue light may promote the synthesis and accumulation of photosynthetic pigments by regulating the expression of photosynthesis-related genes [19]. Chlorophyll A is the most important photosynthetic pigment, and its content directly reflects the plant's photosynthetic efficiency [20]. In this study, the chlorophyll A content of Didymodon tectorum under 24-hour blue light treatment reached 0.228 mg/g FW, significantly higher than that of other light treatments. Additionally, proline, as an important osmotic regulator, helps moss plants cope with drought, salinity, and other stress conditions, and blue light significantly increased proline content, indicating its role in enhancing moss stress resistance [21]. These results suggest that blue light has significant application value in improving the ecological adaptability and stress resistance of moss, particularly in ecological restoration in barren soils or harsh environments. Green light significantly increased superoxide dismutase (SOD) activity under short photoperiods, indicating its role in enhancing moss antioxidant capacity. SOD is a key enzyme in the plant antioxidant system, responsible for scavenging superoxide radicals and protecting cells from oxidative damage [22]. This study found that SOD activity in Didymodon tectorum under 8-hour green light treatment reached 28.817 $U \cdot mg^{-1}$, significantly higher than that of other light quality treatments. Existing studies suggest that green light may enhance moss's ability to scavenge reactive oxygen species by regulating the expression of antioxidant enzyme genes, thereby improving its tolerance to oxidative stress [19]. This finding provides new insights for the application of moss in the remediation of polluted soils or high salinity environments. Green light treatment can optimize the antioxidant capacity of moss, improving its survival rate under stress conditions. Furthermore, the extension of the photoperiod significantly enhanced the regulatory effects of light quality on moss physiological characteristics. For example, under 24-hour red light and blue light treatments, both growth indicators and photosynthetic pigment content were significantly higher than under short photoperiods [23]. This suggests that in the artificial propagation and cultivation of moss, not only the appropriate light quality should be selected, but the photoperiod should also be optimized to achieve efficient growth and enhanced stress resistance [24]. Red light had the most significant promoting effect on moss growth under the 24-hour photoperiod, while blue light was most effective in promoting the accumulation of photosynthetic pigments and proline under the 24-hour photoperiod. Green light was effective in enhancing the antioxidant capacity of moss under the 8-hour photoperiod. The phase-dependent decision workflow translates these physiological responses into actionable cultivation strategies. While red light optimally promotes establishment-phase biomass, the antioxidant-enhancing effects of blue/green light provide targeted solutions for mature-phase stress management. This aligns with modular control frameworks in precision horticulture. These findings provide important references for artificial light control of moss. However, this study primarily focused on moss physiological responses under laboratory conditions. Future research should focus more on the growth performance of moss plants under natural conditions, especially their potential applications in ecological restoration and environmental monitoring [25]. For example, further research could explore moss plants' ability to absorb and fix soil nutrients and heavy metals, as well as the role of mulching in ecological restoration in mining areas. Additionally, future studies could refine the wavelength ranges of light qualities to investigate the effects of specific wavelengths on moss physiology and growth, thus providing more precise guidelines for artificial light control in moss cultivation [26]. The decision logic connects laboratory-scale observations to field applications through phase-specific light response categorization. This framework organizes physiological data into operational protocols compatible with existing precision agriculture systems. Integration with real-time stress monitoring may further enhance the workflow's adaptability. By combining more basic and applied research, we can not only deepen the understanding of the ecological adaptation mechanisms of moss plants but also promote their wide application in environmental governance, ecological restoration, and landscape greening, contributing to the sustainable development of the global ecological environment [27].

V. CONCLUSION

This comprehensive study systematically characterized the differential regulatory effects of light quality and photoperiod on the growth, photosynthetic efficiency, and antioxidant systems of three moss species, providing essential foundational data for their tailored cultivation as bio-materials for sectors such as the sustainable industry. The results provide a crucial physiological foundation for optimizing moss cultivation protocols. Specifically, Red light combined with a 24-hour photoperiod proved to be the most effective regime for promoting vegetative growth, achieving optimal height and coverage by likely stimulating cell division and hormone signaling. Conversely, Blue light at a 24-hour duration demonstrated superiority in enhancing photosynthetic capacity, significantly maximizing chlorophyll a and carotenoid content, while also dramatically increasing Proline accumulation, underscoring its pivotal role in boosting the mosses' stress tolerance and osmotic regulation. Furthermore, Green light, particularly under a short 8-hour photoperiod, elicited the highest Superoxide

Dismutase (SOD) activity, highlighting its specific function in enhancing the moss's immediate antioxidant defenses.

These findings validate the concept of phase-specific light optimization. For biomass establishment, a Red light-dominant, continuous photoperiod is recommended, whereas for enhancing ecological adaptability and stress resistance in the mature phase, Blue or Green light treatments are more appropriate. Crucially, the standardized, high-resolution dataset generated from the 45 experimental treatments bridges the gap between fundamental plant physiology and applied ecological engineering. This dataset forms the basis for a Computational Decision Framework, enabling the development of predictive models and smart cultivation systems. By translating complex light-moss interactions into actionable protocols, this research not only deepens the understanding of moss adaptation mechanisms but also provides data-driven tools essential for scaling up moss propagation and maximizing their success in demanding ecological restoration projects, as well as in providing a sustainable, high-yield source of bio-materials for green industrial applications, ultimately contributing to global environmental sustainability.

AUTHOR CONTRIBUTIONS

Conceptualization –Yufeng Pei, Jianyu Yang, Puhao Liu, Jiani Han and Chao Feng; methodology – Yufeng Pei, Jianyu Yang, Puhao Liu, Jiani Han and Chao Feng; investigation – Yufeng Pei, Jianyu Yang, Puhao Liu, Jiani Han and Chao Feng; writing-original draft preparation – Yufeng Pei, Jianyu Yang, Puhao Liu, Jiani Han and Chao Feng. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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