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Adaptation of Tropical Forage Grasses to Moderate Shade in Coal Mine Reclamation Systems

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Abstract. *Coal mining activities in East Kalimantan have significantly contributed to regional economic development, but they have also resulted in extensive land degradation that requires effective reclamation strategies. The integration of forage crops in reclaimed mine lands offers an opportunity to simultaneously support ecological restoration and livestock production. However, the performance of forage grasses under shaded conditions created by revegetation trees remains insufficiently understood. This study aimed to evaluate the physiological responses, morphological characteristics, and nutritional quality of two forage grass species, Brachiaria humidicola and Stenotaphrum secundatum, grown under shaded conditions on reclaimed coal mine land. The experiment was conducted at the PT Kitadin Embalut reclamation site, East Kalimantan, using a split-plot design with two shading levels (0% and 50%) as the main plots and two grass species as subplots. Each treatment was replicated six times. Variables measured included dry matter yield, leaf-to-stem ratio, chlorophyll content (a, b, and total), crude protein, and crude fiber content. The results showed that a 50% shading level significantly influenced physiological and morphological responses of the grasses. Stenotaphrum secundatum exhibited a marked increase in chlorophyll content under shaded conditions, indicating a stronger acclimation to low light environments compared with Brachiaria humidicola. Shading also reduced the leaf-to-stem ratio in both species. However, dry matter production was not significantly affected by shading, suggesting that both grasses were able to maintain biomass accumulation under moderate shade conditions. Shading slightly reduced crude protein and crude fiber contents.*

Keywords: *Coal mine reclamation, Forage grass, Shade tolerance, Silvopastoral systems, Tropical pasture*

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INTRODUCTION

East Kalimantan is one of the regions in Indonesia with relatively large coal reserves. According to a report from the Ministry of Energy and Mineral Resources (2018), out of Indonesia's total coal reserves of approximately 26.2 billion tons, about 7.5 billion tons are located in East Kalimantan. Coal production in this province reached 305.48 million tons in 2022 and increased to 338.50 million tons in 2023 (Badan Pusat Statistik Kalimantan Timur, 2025). The coal mining sector contributes significantly to the regional economy, accounting for approximately 47% of regional revenue. Despite its substantial economic contribution, coal mining activities also generate various environmental impacts, including the loss of agricultural and forest land, decline in biodiversity, contamination of water bodies, degradation of soil structure, and potential health risks for communities living near mining areas (Aleksandrova & Timofeeva, 2021; Paredes-Vilca et al., 2024; Talukder et al., 2023). Therefore, the government requires mining companies to implement land reclamation programs to restore the ecological and social functions of areas disturbed by mining operations (Indrayanti, 2023; Pratiwi et al., 2021).

Land reclamation refers to activities carried out during and after mining operations to reshape the land, restore environmental quality, and rehabilitate ecosystems so that they can function again according to their intended use (Law of the Republic of Indonesia No. 3 of 2020; Strzałkowski & Kaźmierczak, 2019). From an ecological perspective, reclamation aims to stabilize the land surface, restore soil fertility, and re-establish a functioning and sustainable ecological system (Gaćina et al., 2024; Xiaoying, 2023). In practice, reclamation activities not only involve land reshaping but also revegetation through the establishment of ground cover plants, fast-growing species, and local vegetation. Ground cover plants play an important role in reducing soil erosion, increasing soil organic matter, and gradually improving the physical, chemical, and biological properties of soil (Blanco-Canqui & Ruis, 2020). Furthermore, the use of forage crops as ground cover can provide additional economic value through the utilization of reclaimed mine land for livestock production (Daru et al., 2020).

However, forage species used in reclamation areas must possess strong adaptability to limited environmental conditions, including low soil fertility and shaded environments caused by revegetation trees (Daru et al., 2023; Grimoldi & Bella, 2024). Therefore, identifying forage grass species that are tolerant to shade is essential to support successful revegetation while maintaining forage productivity.

This study aimed to evaluate the physiological responses, morphological characteristics, and nutritional quality of two forage grass species, *Brachiaria humidicola* and *Stenotaphrum secundatum*, grown under open conditions and under the shade of revegetation trees on reclaimed coal mine land. The findings of this study are expected to provide scientific information on the potential use of forage grasses as adaptive ground cover plants in post-mining land reclamation systems.

LITERATURE REVIEW

Reclamation describes a process in which the land surface is restored to forms that are beneficial and consistent with ecological principles that promote recovery (Shao et al., 2023). The main objectives of reclamation are to stabilize the land surface, ensure public safety, improve aesthetics, and generally return the land, within a regional context, to beneficial uses (Setiawan et al., 2021). It has also been stated that the most important activities in post-mining land reclamation include: (1) the establishment of forage plants intended to support habitats for livestock or wildlife that previously existed in the area, and (2) the control of soil erosion (Shao et al., 2023; Tripathi et al., 2025). The establishment of forage plants, such as grasses and legumes, can function both as erosion control and as a means of stabilizing mine spoil. Open land surfaces may increase surface runoff, which can reduce groundwater surface quality and aesthetic value (Jia et al., 2020). Such conditions are usually accompanied by declining soil fertility, low soil moisture, and high soil surface temperatures. Therefore, the initial step in mine land reclamation is commonly the establishment of cover crops using forage species (Anda et al., 2022).

The establishment of cover crops during the early stage of reclamation generally utilizes plant species that have high adaptability to nutrient-poor soils as well as tolerance to shaded conditions (Kumari & Maiti, 2021). These plants not only protect the soil surface from erosion and increase soil organic matter content, but also gradually improve the physical, chemical, and biological properties of the soil (Blanco-Canqui & Ruis, 2020). Forage crops planted on reclamation land may also serve as a source of green fodder for livestock, thereby providing added value for the productive utilization of post-mining land (Zhang et al., 2025). Thus, the use of forage plants as cover crops in post-mining land reclamation not only contributes to environmental restoration but also supports the development of sustainable agricultural and livestock production systems (Shao et al., 2023).

The establishment of forage crops under the shade of revegetation plants may influence the growth and productivity of the forage species growing beneath them. Experimental results reported by dos Santos Neto et al. (2023) showed that the grasses *Urochloa mosambicensis*, *Pennisetum ciliare*, and *Megathyrsus maximus* experienced a reduction in tiller number when grown under 46% shade. Similarly, research conducted by Lista et al. (2019) indicated that increasing shade levels from 0% to 70% reduced dry matter production, increased the leaf-to-stem ratio, and increased crude protein content in the legumes *Neonotonia wightii*, *Pueraria phaseoloides*, *Macrotyloma axillare*, and *Arachis pintoi*. Based on these findings, it is necessary to identify forage species that are tolerant to shade under post-mining reclamation conditions, so that forage production can be maintained both quantitatively and qualitatively.

RESEARCH METHODS

The experiment was conducted on post-coal mining reclamation land PT Kitadin, Site Embalut, Tenggarong Seberang Subdistrict, Kutai Kartanegara Regency, using two types of grass, namely *Stenotaphrum secundatum* and *Brachiaria humidicola*, which were planted in the form of pols. The study was designed as a split plot, with shade level as the main plot consisting of an open location (S0) and under wild eugenia (*Eugenia* sp.) as revegetation plants (S1), while the grass type as the subplot consisted of S. secundatum (V1) and B. humidicola (V2). Each experimental plot measured 3 m × 3 m and was replicated by six times. Before planting, the soil was tilled and fertilised with cow manure compost of 20 tonnes ha^{-1}. The grass was then planted at a spacing of 50 cm × 50 cm. Plant maintenance included watering, weeding and manual weed removal. The initial cutting was carried out 60 days after planting at a height of 10 cm above the soil surface, while subsequent cuttings were carried out every 40 days for a total of three cuttings for data collections.

The variables observed included plant dry weight, leaf/stem ratio, chlorophyll a, b, and total, as well as crude protein and crude fibre content. In measuring chlorophyll content, a spectrophotometer was used with 80% acetone as the solvent for extracting chlorophyll from the leaf samples. The determination of chlorophyll content followed the equations proposed by Porra (2002), namely: chlorophyll a (μg/ml) = 12.25 (A663.6) − 2.55 (A646.6), chlorophyll b (μg/ml) = 20.31 (A646.6) − 4.91 (A663.6), and total chlorophyll (μg/ml) = 17.76 (A646.6) + 7.34 (A663.6). Light intensity was measured using a lux meter every week at 08:00, 12:00, and 16:00. To determine the percentage of shade, the following formula was used: shade (%) = 100 − (radiation under canopy / radiation in open area × 100%) (Monteith & Unsworth, 2008). The data were analysed by analysis of variance (ANOVA) using IBM SPSS Statistics software. When significant differences were observed, mean comparisons were performed using Duncan's Multiple Range Test at a 5% significance level.

RESULTS AND DISCUSSION

1. Chlorophyll

Based on measurements of solar radiation intensity beneath the canopy of revegetation trees and in open areas, the shading level under the revegetation canopy was estimated to be approximately 50%. This level of shading created a distinct microenvironment that influenced the physiological responses of the studied forage grasses.

Shading significantly affected the chlorophyll content of grass leaves. In *Stenotaphrum secundatum*, increasing shade levels resulted in higher concentrations of chlorophyll *a*, chlorophyll *b*, and total chlorophyll. This response indicates a physiological acclimation mechanism to low-light conditions, in which plants increase chlorophyll synthesis to enhance light absorption and maintain photosynthetic efficiency. Such adjustments are commonly observed in shade-tolerant species as part of their strategy to optimize light harvesting under reduced irradiance (Poorter et al., 2021; Wang et al., 2022). Increasing chlorophyll content under shaded conditions allows plants to improve photon capture and sustain carbon assimilation when light availability becomes a limiting factor (Li et al., 2023).

In contrast, *Brachiaria humidicola* showed an opposite trend, where increasing shade levels resulted in a decrease in chlorophyll content (Table 1). This reduction suggests a more limited physiological adjustment to reduced light availability, indicating that this species may be less capable of enhancing photosynthetic pigment concentrations under shaded environments. Similar findings have been reported in several tropical forage grasses, where species with lower shade tolerance tend to exhibit reduced chlorophyll accumulation and photosynthetic performance under reduced irradiance (Dias-Filho, 2020; Paciullo et al., 2021).

The contrasting responses observed between the two species highlight differences in their adaptive strategies to shaded environments. The ability of *S. secundatum* to increase chlorophyll concentration under moderate shading suggests a stronger capacity for physiological acclimation, which may provide an advantage in environments where light availability is partially limited by tree canopy cover. Therefore, this species may be more suitable for integration into revegetation systems or silvopastoral landscapes where moderate shading occurs.

Table 1. Chlorophyll content of *S. secundatum* and *B. humidicola* under different shading levels.

Grass species	Chl a (µg mL^{-1})		Chl b (µg mL^{-1})		Chl total (µg mL^{-1})	
	0% shading	50% shading	0% shading	50% shading	0% shading	50% shading
S. secundatum	0.33 ± 0.00^{aA}	0.72 ± 0.09^{bB}	0.25 ± 0.03^{aA}	1.38 ± 0.07^{bB}	0.59 ± 0.06^{aA}	0.59 ± 0.06^{aA}
B. humidicola	0.40 ± 0.11^{aB}	0.22 ± 0.02^{aA}	0.44 ± 0.06^{bA}	0.51 ± 0.06^{aA}	0.83 ± 0.02^{bA}	0.83 ± 0.02^{bA}

Note: Chl = chlorophyll. Values are presented as mean ± standard deviation. Means followed by the same lowercase letters within rows and the same uppercase letters within columns are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

Light is a critical environmental factor influencing plant physiological growth; therefore, plants require appropriate light intensity to support optimal growth and development. Exposure to excessively high light intensity may lead to excess excitation energy, which can reduce photochemical efficiency and induce photoinhibition, thereby negatively affecting plant health (Xue et al., 2023).

Physiologically, the increase in chlorophyll *a* observed in shaded plants represents a common acclimation response to reduced light availability, as plants attempt to maintain their capacity for energy capture during photosynthesis. Recent studies indicate that plants exposed to low-light stress generally adjust their photosynthetic systems through modifications in pigment composition, light-harvesting efficiency, and the reorganization of chloroplast apparatus (Khan et al., 2025). The response observed in *Stenotaphrum secundatum* in the present study is consistent with the findings of Sembiring, Witariadi, and Wirawan (2024), who reported that moderate shading could enhance leaf color and chlorophyll content in *S. secundatum*, although excessive shading may suppress plant growth. In contrast, the declining response of *Brachiaria humidicola* under shaded conditions indicates a more limited pigment acclimation capacity. This observation supports the notion that in C4 grasses, responses to shading are highly genotype-specific and may vary considerably among genera and species (Andrade et al., 2024; Wang et al., 2024).

The stronger increase in chlorophyll *b* observed in *S. secundatum* is physiologically significant because chlorophyll *b* plays a major role in the light-harvesting complex, particularly when plants must maximize photon absorption under low-light environments. Recent literature indicates that many plants under shaded conditions tend to increase chlorophyll *b* accumulation and reduce the chlorophyll *a/b* ratio in order to improve light capture efficiency (Khan et al., 2025). Similarly, the review by Elango et al. (2023) reported that reduced light intensity is often associated with increased chlorophyll concentration and changes in pigment composition as a strategy to enhance photosynthetic efficiency. Therefore, the pronounced increase in chlorophyll *b* in *S. secundatum* may indicate that this species possesses a stronger shade-acclimation capacity. Conversely, *B. humidicola* appeared relatively stable or less responsive in terms of chlorophyll *b* content, suggesting a more limited capacity to adjust to low-light stress under the conditions of this study.

Total chlorophyll content is widely used as an indicator of light absorption capacity and the physiological status of plant leaves. In shaded environments, an increase in total chlorophyll generally reflects a compensatory strategy to maintain photosynthetic performance under reduced radiation levels. Research by Wang et al. (2024) on C4 grasses demonstrated that shade acclimation involves comprehensive adjustments in photosynthetic traits, leaf anatomy, and light-use efficiency. Andrade et al. (2024) also emphasized that C4 grass species may exhibit contrasting strategies under shading conditions, with some species enhancing light-harvesting capacity while others display more conservative responses. More broadly, Paszkiewicz-Jasińska et al. (2026) reported that chlorophyll content in grasses shows high metabolic plasticity and is strongly influenced by environmental conditions. Therefore, the higher total chlorophyll observed in *S. secundatum* in the present study may reflect its greater acclimation capacity to shaded environments compared with *B. humidicola*.

2. Leaf-Stem Ratio

The leaf:stem ratio was significantly affected by shading level and grass species, whereas the interaction between these two factors was not significant. The mean leaf:stem ratio was higher under 0% shading compared with 50% shading. Based on species means, *Brachiaria humidicola* exhibited a higher leaf:stem ratio than *Stenotaphrum secundatum.* These results indicate that shaded conditions reduced the proportion of leaves relative to stems, and this decreasing pattern occurred similarly in both species (Table 2).

Table 2. Leaf–stem ratio of *Stenotaphrum secundatum* and *Brachiaria humidicola* under different shading levels.

Grass species	0% shading	50% shading	Means
S. secundatum	1.34 ± 1.16	0.62 ± 0.13	0.98 ± 0.87[a]
B. humidicola	3.10 ± 1.59	0.99 ± 0.24	2.04 ± 1.55[b]
Means	2.22 ± 1.61[b]	0.80 ± 0.27[a]	1.51 ± 1.34

Note: Values are presented as mean ± standard deviation. Means followed by different lowercase letters within rows and different letters within columns indicate significant differences at P < 0.05 according to Duncan's Multiple Range Test.

The reduction in the leaf:stem ratio under shaded conditions suggests morphological adjustments in plant growth in response to limited light availability. Under reduced irradiance, plants often allocate more resources to stem elongation as an adaptive strategy to enhance light interception, which consequently decreases the relative proportion of leaves. Similar responses have been widely reported in forage grasses grown under shaded environments, where shade-induced stem elongation leads to structural changes in canopy architecture (Paciullo et al., 2021; Andrade et al., 2024). Such morphological plasticity represents a common strategy for plants to optimize light capture when light becomes a limiting resource.

Differences between species further indicate variation in morphological adaptation to shading. The higher leaf:stem ratio observed in *B. humidicola* suggests that this species maintains a relatively greater leaf proportion compared with *S. secundatum*, which may influence forage quality and canopy structure. Previous studies have shown that species-specific responses in leaf allocation are common among tropical forage grasses, reflecting differences in growth strategies and shade tolerance (Dias-Filho, 2020; Wang et al., 2024). Therefore, the contrasting responses observed in this study highlight the importance of species selection when integrating forage grasses into shaded environments such as revegetation areas or silvopastoral systems.

3. Dry Matter Production

The analysis of variance indicated that shading level, grass species, and their interaction did not significantly affect the dry matter production of the grasses (Table 3). This result suggests that both *Stenotaphrum secundatum* and *Brachiaria humidicola* were able to maintain biomass accumulation under moderate shading conditions, indicating a relatively good level of tolerance to reduced light availability.

Table 3. Dry matter production of *Stenotaphrum secundatum* and *Brachiaria humidicola* under different shading levels.

Grass species	0% shading (g plot^{-1})	50% shading (g plot^{-1})	Means (g plot^{-1})
S. secundatum	42.17 ± 28.30	73.17 ± 43.80	57.67 ± 38.70
B. humidicola	89.83 ± 39.92	83.33 ± 77.31	86.58 ± 58.76
Means	66.00 ± 41.33	78.25 ± 60.14	72.13 ± 50.85

Note: Values are presented as mean ± standard deviation.

The absence of a significant effect of shading on dry matter production indicates that both grass species were able to maintain biomass accumulation under different environmental conditions. This finding is consistent with reports by Dazaea et al. (2025) and Díaz et al. (2025), which state that the effects of shading on forage production are not always consistent, as they are strongly influenced by shading intensity, light distribution, microclimatic conditions, and the adaptive capacity of the species involved. In agrivoltaic systems, high levels of shading may reduce forage yield; however, under certain conditions, production can remain stable or even increase in zones with improved soil moisture and more moderate canopy temperatures.

A meta-analysis of tropical grasslands further indicates that both productivity and forage quality are simultaneously influenced by environmental conditions and management practices, resulting in variable dry matter yield responses across species and environments (Jayasinghe et al., 2022). Therefore, the lack of a significant response in dry matter production under shading levels of up to 50% observed in this study may reflect an adaptive response to the prevailing microclimatic conditions and other growth-related factors.

4. Crude Protein and Crude Fiber Content

The crude protein (CP) and crude fiber (CF) contents were significantly influenced by both shading level and grass species, whereas the interaction between these factors was not significant (Table 4). This indicates that the effects of shading and species differences on forage nutritional quality occurred independently.

Table 4. Crude protein (CP) and crude fiber (CF) contents of *Stenotaphrum secundatum* and *Brachiaria humidicola* under different shading levels.

Grass species	CP (%)			CF (%)		
	0% shading	50% shading	Rataan	0% shading	50% shading	Means
S. secundatum	6.77 ± 0.40	6.42 ± 0.07	6.59 ± 0.32^{a}	35.09 ± 0.62	34.01 ± 0.12	34.55 ± 0.71^{a}
B. humidicola	8.18 ± 0.26	7.54 ± 0.10	7.86 ± 0.38^{b}	36.69 ± 0.36	35.18 ± 0.18	35.93 ± 0.83^{b}
Means	7.47 ± 0.80^{b}	6.98 ± 0.59^{a}	7.23 ± 0.73	35.89 ± 0.97^{b}	34.59 ± 0.63^{a}	35.24 ± 1.04

Note: Values are presented as mean ± standard deviation. Means followed by different lowercase letters within rows or columns indicate significant differences at P < 0.05 according to Duncan's Multiple Range Test.

In general, crude protein (CP) content is influenced by plant species, plant age, environmental conditions, and defoliation management. A meta-analysis of tropical grasslands demonstrated that CP content varies considerably among species and locations and is strongly affected by climatic conditions and management practices (Jayasinghe et al., 2022). Similarly, evaluations of several *Brachiaria* species have revealed significant differences in CP content among species, indicating that certain genotypes possess a greater capacity for protein production than others (Tiruneh et al., 2023).

On the other hand, studies conducted in silvopastoral systems have reported that shading can sometimes increase protein content by improving the microclimate and slowing tissue maturation. Díaz et al. (2025), for example, reported higher CP content in *Brachiaria decumbens* under shaded conditions. Similar observations were reported by Ripamonti et al. (2025), who noted that forage grasses may exhibit increased CP concentrations under shaded environments in certain cases. However, the results of the present study showed that CP content was higher under full sunlight conditions, with *Brachiaria humidicola* exhibiting higher CP content than *Stenotaphrum secundatum*.

Grasses growing under shaded conditions experience reduced light intensity, which can lower photosynthetic rates and consequently reduce the availability of energy and carbon required for plant metabolic processes, including amino acid and protein synthesis (Hu et al., 2025). In addition, plants growing under shaded environments often exhibit morphological adaptations known as the *shade avoidance syndrome*, such as stem or internode elongation and increased leaf area. These adaptations tend to allocate a greater proportion of biomass to stem growth, which may reduce dry matter accumulation and decrease nutrient concentrations, including protein per unit of dry matter (Tang et al., 2022).

Crude fiber (CF) represents the structural component of plant tissues and generally increases with plant physiological maturity and with a higher proportion of stems in the canopy. Therefore, changes in CF content are often associated with morphological changes in plant canopy structure. Under shaded conditions, reduced light intensity can decrease photosynthetic rates, thereby limiting the production and accumulation of photosynthates. These carbohydrates serve as precursors for the formation of structural cell wall components such as cellulose and hemicellulose; thus, limited carbon availability may reduce fiber accumulation in plant tissues (Tang et al., 2022).

Jayasinghe et al. (2022) reported that fiber components in tropical forages vary substantially among species and are strongly influenced by environmental conditions, while Wróbel et al. (2025) emphasized that forage quality generally improves when the proportion of structural fiber is lower. In the present study, the reduction in CF under shaded conditions, which corresponded with reduced light intensity, may have limited the formation of certain structural tissues. In general, the fiber content of grasses tends to remain stable or decrease under shaded environments (Ripamonti et al., 2025). However, because CP content also declined under shaded conditions in this study, the forage grown under shade cannot yet be considered nutritionally superior. Therefore, shading should be viewed primarily as a factor that alters the structural composition of forage rather than consistently improving its overall nutritional quality.

CONCLUSION

The results of this study indicate that a shading level of approximately 50% under wild Wild *Eugenia* (*Eugenia* sp.) revegetation trees on reclaimed coal mine land significantly influenced the physiological responses, morphological characteristics, and forage nutritional quality of the two tested grass species. *Stenotaphrum secundatum* exhibited an increase in chlorophyll content as an acclimation response to reduced light intensity, whereas *Brachiaria humidicola* showed a more limited physiological response. Shading also reduced the leaf-to-stem ratio in both species, indicating morphological adjustments that enable plants to improve light capture under shaded conditions. However, shading levels of up to 50% did not significantly affect dry matter production, suggesting that both grasses were able to maintain biomass accumulation under moderate shade conditions. In terms of forage quality, shading resulted in lower crude protein and crude fiber contents, which were likely associated with changes in carbon metabolism and the formation of structural plant tissues. Overall, both grass species demonstrated good adaptability to moderate shade conditions, indicating their potential use as forage crops as well as ground cover plants in post-mining land reclamation systems.

These findings provide important implications for the management of post-mining land reclamation and the development of silvopastoral systems. The ability of *Stenotaphrum secundatum* and *Brachiaria humidicola* to maintain biomass production under moderate shading suggests that these species can be utilized as ground cover and forage resources in reclaimed lands planted with revegetation trees. Integrating forage plants beneath tree stands may not only accelerate ecological recovery through erosion control and increased soil organic matter but also enhance land productivity through crop–livestock integration systems. Therefore, the selection of shade-tolerant forage species represents an important strategy for improving revegetation success and supporting sustainable management of reclaimed mine lands.

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REFERENCES

Aleksandrova, A. Y., & Timofeeva, S. S. (2021). Impact of mining of common minerals on the environment and public health. *IOP Conference Series: Earth and Environmental Science, 848*(1), 012136. https://doi.org/10.1088/1755-1315/848/1/012136

Anda, M., Diah, N., Purwantari, D., Yulistiani, D., Sajimin, S., Suryani, E., Husnain, H., & Agus, F. (2022). Reclamation of post-tin mining areas using forages: A strategy based on soil mineralogy, chemical properties and particle size of the refused materials. *Catena, 213*, 106140. https://doi.org/10.1016/j.catena.2022.106140

Andrade, E. S., Souza, B. C. O. Q., Costa, E. P., Bonezio, H., Assefa, M. K., Pires-Lira, M. F., Morais, L. E., Marchiori, P. E. R., & Nascimento, V. L. (2024). Distinct morphophysiological responses of the native C4 grasses *Axonopus siccus* and *Eragrostis polytricha* to shading. *Flora, 320,* 152621. https://doi.org/10.1016/j.flora.2024.152621

Blanco-Canqui, H., & Ruis, S. J. (2020). Cover crop impacts on soil physical properties: A review. *Soil Science Society of America Journal, 84*(5), 1527–1576. https://doi.org/10.1002/saj2.20129

da Silva, I. A. G., Dubeux, J. C. B., Jr., Santos, M. V. F., de Mello, A. C. L., Cunha, M. V., Apolinário, V. X. O., & de Freitas, E. V. (2021). Tree canopy management affects dynamics of herbaceous vegetation and soil moisture in silvopasture systems using arboreal legumes. *Agronomy, 11*(8), 1509. https://doi.org/10.3390/agronomy11081509

Daru, T. P., Sunaryo, W., Pagoray, H., Suhardi, S., Mayulu, H., Ibrahim, I., & Safitri, A. (2023). Diversity, nutrient contents and production of forage plants in an integrated cattle livestock–oil palm plantation in East Kalimantan, Indonesia. *Biodiversitas, 24*(4), 1980–1988. https://doi.org/10.13057/biodiv/d240406

Daru, T. P., Yusuf, R., & Juraemi, J. (2020). Potensi tumbuhan di lahan reklamasi pasca tambang batubara sebagai pakan ternak. *Jurnal Pertanian Terpadu, 8*(2), 164–174. https://doi.org/10.36084/jpt.v8i2.273

Dazaea, A., Higgins, C., Rosati, A., Graham, M., & Ates, S. (2025). The effect of establishment method and shade zones within solar arrays on pasture production in agrivoltaics production system. *Frontiers in Sustainable Food Systems, 9*, 1637340. https://doi.org/10.3389/fsufs.2025.1637340

Dey, P., Pattanaik, D., Dash, D., Singhal, R. K., Gaikwad, D. J., Baig, M. J., Kumar, R., Lone, A. A., & Rahimi, M. (2025). Mechanisms of low light stress in rice: Current insights and future directions. *Plant Growth Regulation, 105*, 1949–1968. https://doi.org/10.1007/s10725-025-01396-2

Dias-Filho, M. B. (2020). Growth and biomass allocation of tropical forage grasses under shade conditions. *Grass and Forage Science*, 75(3), 235–245. https://doi.org/10.1111/gfs.12478

Díaz, M., Alegre, J., Gómez, C., García, C., & Arévalo-Hernández, C. (2025). Effect of light on yield, nutritive value of *Brachiaria decumbens*, and soil properties in silvopastoral systems, Peruvian Amazon. *Grasses, 4*(2), 18. https://doi.org/10.3390/grasses4020018

Dong, L., Xiong, L., Sun, X., Shah, S., Guo, Z., Zhao, X., Liu, L., Cheng, L., Tian, Z., Xie, F., & Chen, Y. (2022). Morphophysiological responses of two cool-season turfgrasses with different shade tolerances. *Agronomy, 12*(4), 959. https://doi.org/10.3390/agronomy12040959

dos Santos Neto, C. F., da Silva, R. G., Maranhão, S. R., Cavalcante, A. C. R., Macedo, V. H. M., & Cândido, M. J. D. (2023). Shading effect and forage production of tropical grasses in Brazilian semi-arid silvopastoral systems. *Agroforestry Systems, 97*, 995–1005. https://doi.org/10.1007/s10457-023-00843-1

Elango, T., Jeyaraj, A., Dayalan, H., Arul, S., Govindasamy, R., Prathap, K., & Li, X. (2023). Influence of shading intensity on chlorophyll, carotenoid and metabolites biosynthesis to improve the quality of green tea: A review. *Energy Nexus, 12*, 100241. https://doi.org/10.1016/j.nexus.2023.100241

Gaćina, R., Bajić, S., Dimitrijević, B., & Gluščević, B. (2024). Criteria for decision-making for the best reclamation solution. *Underground Mining Engineering, 45*, 105–113. https://doi.org/10.5937/podrad2445105g

Grimoldi, A. A., & Di Bella, C. E. (2024). Forage plant ecophysiology under different stress conditions. *Plants, 13*, 1302. https://doi.org/10.3390/plants13101302

Hu, Y., Javed, H. H., Liu, L., Liu, Y., Yang, X., Xu, F., Liu, Y., Peng, X., & Wu, Y. (2025). Impact of low light on photosynthetic characteristics, antioxidant activity, and yield of *Brassica napus* L. *Agronomy, 15*, 214. https://doi.org/10.3390/agronomy15010214

Indrayanti, K. W. (2023). Law enforcement of reclamation and post coal mining policy in East Kalimantan Province, Indonesia. *International Journal of Social Science Research and Review, 6*(1), 10–20. https://doi.org/10.47814/ijssrr.v6i1.717

Jayasinghe, P., Ramilan, T., Donaghy, D. J., Pembleton, K. G., & Barber, D. G. (2022). Comparison of nutritive values of tropical pasture species grown in different environments and implications for livestock methane production: A meta-analysis. *Animals, 12*(14), 1806. https://doi.org/10.3390/ani12141806

Jiang, K., Yang, Z., Sun, J., Liu, H., Chen, S., Zhao, Y., Xiong, W., Lu, W., Wang, Z. Y., & Wu, X. (2022). Evaluation of the tolerance and forage quality of different ecotypes of seashore paspalum. *Frontiers in Plant Science, 13*, 944894. https://doi.org/10.3389/fpls.2022.944894

Khan, I., Sohail, S., Zaman, S., Li, G., & Fu, M. (2025). Adaptive responses of plants to light stress: Mechanisms of photoprotection and acclimation. *Frontiers in Plant Science, 16*, 1550125. https://doi.org/10.3389/fpls.2025.1550125

Kumari, S., & Maiti, S. K. (2022). Grass-legume seeding: A sustainable approach towards reclamation of coalmine degraded lands in India. In *Legumes Research*. IntechOpen. https://doi.org/10.5772/intechopen.99741

Li, Y., Zhang, X., Chen, H., & Wang, Z. (2023). Physiological responses of plants to low light stress and adaptive mechanisms. *Plants*, 12(4), 745. https://doi.org/10.3390/plants12040745

Lista, F. N., Deminicis, B. B., Almeida, J. C. C., Araujo, S. A. C., & Zane, P. G. (2019). Forage production and quality of tropical forage legumes submitted to shading. *Ciência Rural, 49*(7), e20170726. https://doi.org/10.1590/0103-8478cr20170726

Monteith, J., & Unsworth, M. (2008). *Principles of environmental physics* (3rd ed.). Elsevier.

Paciullo, D. S. C., Gomide, C. A. M., Castro, C. R. T., Maurício, R. M., & Fernandes, P. B. (2021). Forage production and nutritive value in silvopastoral systems under different shading levels. *Agroforestry Systems*, 95, 1167–1178. https://doi.org/10.1007/s10457-021-00633-2

Poorter, H., Niinemets, Ü., Ntagkas, N., et al. (2021). A meta-analysis of plant responses to light intensity for photosynthesis, morphology, and biomass allocation. *New Phytologist*, 231, 1923–1935. https://doi.org/10.1111/nph.17503

Porra, R. J. (2002). The chequered history of the development and use of simultaneous equations for the accurate determination of chlorophylls a and b. *Photosynthesis Research, 73*, 149–156.

Pratiwi, B. H., Narendra, B. H., Siregar, C. A., Turjaman, M., Hidayat, A., Rachmat, H. H., Mulyanto, B., Suwardi, S., Iskandar, I., & Maharani, R. (2021). Managing and reforesting degraded post-mining landscape in Indonesia: A review. *Land, 10*, 658. https://doi.org/10.3390/land10060658

Shao, Y., Xu, Q., & Wei, X. (2023). Progress of mine land reclamation and ecological restoration research based on bibliometric analysis. *Sustainability, 15*, 10458. https://doi.org/10.3390/su151310458

Tang, W., Guo, H., Baskin, C. C., Xiong, W., Yang, C., Li, Z., Song, H., Wang, T., Yin, J., & Wu, X. (2022). Effect of light intensity on morphology, photosynthesis and carbon metabolism of alfalfa (*Medicago sativa*) seedlings. *Plants, 11*, 1688. https://doi.org/10.3390/plants11131688

Talukder, P., Ray, R., Sarkar, M., & Chakraborty, S. (2023). Adverse effects of mining pollutants on terrestrial and aquatic environment and its remediation. *Environmental Quality Management*. https://doi.org/10.1002/tqem.22121

Wang, Y., Li, X., Zhang, Y., & Liu, Z. (2022). Chlorophyll regulation and photosynthetic acclimation of plants under low light environments. *Frontiers in Plant Science*, 13, 904120. https://doi.org/10.3389/fpls.2022.904120

Wang, G., Mao, J., Ji, M., Wang, W., et al. (2024). A comprehensive assessment of photosynthetic acclimation to shade in C4 grass (*Cynodon dactylon*). *BMC Plant Biology*, *24*, 591. https://doi.org/10.1186/s12870-024-05242-x

Wróbel, B., Zielewicz, W., & Paszkiewicz-Jasińska, A. (2025). Improving forage quality from permanent grasslands to enhance ruminant productivity. *Agriculture, 15,* 1438. https://doi.org/10.3390/agriculture15131438

Wu, W., Chen, L., Liang, R., Huang, S., Li, X., Huang, B., Luo, H., Zhang, M., Wang, X., & Zhu, H. (2025). The role of light in regulating plant growth, development and sugar metabolism: A review. *Frontiers in Plant Science, 15*, 1507628. https://doi.org/10.3389/fpls.2024.1507628

Xiaoying, D. (2023). Land reclamation and soil health in mining area. *Journal of Latin American Sciences and Culture, 5*(8), 72–75. https://doi.org/10.52428/27888991.v5i8.1070

Xue, G., Wu, J., Zhou, B., Zhu, X., Zeng, J., Ma, Y., Wang, Y., & Jia, H. (2023). Effects of shading on the growth and photosynthetic fluorescence characteristics of *Castanopsis hystrix* seedlings. *Forests, 14,* 1659. https://doi.org/10.3390/f14081659

Zhang, Z., Ye, F., Tuo, H., Wang, Y., Li, W., Zeng, Y., & Li, H. (2025). Combining grass-legume mixtures with soil amendments boosts aboveground productivity on engineering spoil through selection and compensation effects. *Diversity*, *17*, 513. https://doi.org/10.3390/d17080513