MEKATRONIKA: JOURNAL OF INTELLIGENT MANUFACTURING AND MECHATRONICS
E-ISSN: 2637-0883
VOLUME 8, ISSUE 1, 2026, In-Press
DOI: https://doi.org/10.15282/mekatronika.v8i2.14788

RESEARCH ARTICLE

# Quantitative evaluation of supplemental LED lighting for Axonopus compressus recovery using ANOVA and growth analysis

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**Abstract:** Urban turfgrass management, particularly for species like Axonopus compressus (Cow Grass), faces significant challenges due to light limitation in high-density built environments such as semi-enclosed stadia. This study investigates the integration of mechatronic principles and supplemental LED lighting to accelerate the recovery of chlorotic turfgrass, comparing natural sunlight exposure against a supplemental red-blue LED grow light system. A red-blue LED grow light system (5000 ± 1000 lumens) was applied nocturnally for three hours to one of two experimental patches over 15 days, with five marked sampling areas per patch; leaf colour, leaf length, leaf width, root/stem length, stem width, and leaf count were recorded on Days 1, 4, 9, and 15 and compared using ANOVA and the Mann–Whitney U test. The LED-treated patch showed a higher colour-recovery rate (0.352 versus 0.274 units day−1; 28.7% improvement) and a lower vertical-growth rate (1.438 versus 1.915 mm day−1; 24.9% lower) than the control; ANOVA identified a statistically significant between-group difference only for leaf length ($p = 0.0395$), with the remaining parameters not significant at $\alpha = 0.05$. Canopy colour and vertical elongation emerge as candidate feedback variables for future closed-loop, energy-aware lighting control, although the present findings should be regarded as preliminary given the small sample size and limited replication.

**Article History**
Received :
Revised :
Accepted :
Published :

**Keywords**
*Axonopus compressus (Cow Grass)*
*Supplemental LED Lighting*
*Closed-Loop Mechatronic Control (Future Work)*
*Mechatronic Systems*
*Precision Turf Management*

## 1. Introduction

Axonopus compressus (Sw.) Beauv., commonly known as cow grass or broadleaf carpet grass, is a warm-season turfgrass used in tropical and subtropical landscapes because of its ground-covering habit and tolerance of moist, periodically shaded sites. In dense urban environments, however, buildings and other structures reduce the amount and duration of photosynthetically active radiation (PAR) reaching the canopy. Insufficient light can reduce chlorophyll accumulation, photosynthetic capacity, biomass production, and turf quality, while also altering leaf morphology and biomass allocation [1], [2]. These effects make the recovery of yellowish or chlorotic turf a practical management problem rather than only a cosmetic concern. Urban green spaces contribute to thermal regulation through shading and evapotranspiration, but their performance depends on maintaining adequate plant cover. In shaded turf, reduced carbon gain may be accompanied by elongated, less robust leaves and reduced root development. A study of tropical turfgrasses found that Axonopus compressus increased relative leaf extension under simulated shade, while green cover and other quality traits declined as shade intensity increased [2]. This response provides a biological basis for comparing leaf-color recovery with vertical elongation rather than treating "more growth" as an unqualified improvement.

Supplemental LED lighting offers a controllable way to compensate for shortfalls in natural light. LEDs can be selected and modulated by intensity, photoperiod, and spectral composition, allowing a lighting treatment to be matched to the recovery objective. Evidence from perennial ryegrass, a widely used sports-turf species, shows that both light intensity and spectral quality influence foliar pigments, photosynthetic performance, biomass accumulation, water use, and energy consumption; an R80:B20 treatment was reported as a compromise between physiological performance and energy demand [3]. Results from other turfgrass species likewise indicate that LED supplementation can improve recovery-related traits under shade, although responses remain species- and intensity-specific [4]. Despite these advances, species-specific evidence for supplemental lighting of Axonopus compressus in urban landscape conditions remains limited. The present study compares naturally illuminated control turf with turf receiving three hours of nocturnal red-blue LED supplementation. The objectives are to quantify short-term changes in leaf color, leaf dimensions, root/stem length, stem width, and leaf count, and to identify the practical implications of these responses for precision turf management. We hypothesize that supplemental LED lighting will accelerate color recovery but may alter vertical growth, producing a measurable trade-off between visual greenness and elongation.

## 2. Literature Review

Precision agriculture has progressed from stand-alone automation toward cyber-physical systems that combine sensors, computation, and actuators [5]. For urban turf management, the relevant control problem is to deliver supplemental light only when the canopy experiences a meaningful light deficit and to adjust the treatment according to plant response. This requires measurements that are practical in the field, such as canopy color, leaf dimensions, ambient illuminance or PPFD, temperature, and soil moisture, rather than relying on a fixed lighting schedule alone. LEDs are attractive for this

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application because they provide high controllability of intensity and spectrum and can be integrated with pulse-width-modulated drivers. Nevertheless, illuminance in lumens is a photometric measure weighted to human vision and is not equivalent to the photon flux used to describe plant lighting. Future experiments should therefore report photosynthetic photon flux density (PPFD, μmol m−2 s−1), daily light integral, lamp distance, beam coverage, and spectral distribution in addition to lumens. These measurements would make the treatment reproducible and would permit energy-use comparisons.

The plant literature also shows why turf-specific validation is necessary. Shade modifies chlorophyll status, photosynthesis, morphology, and root growth, but the magnitude and direction of these responses differ among species and cultivars [1]. In Axonopus compressus, simulated shade increased relative leaf extension while reducing performance indicators such as green cover at high shade levels [2]. Optical sensing and image-based plant assessment can provide non-destructive feedback for monitoring these responses [6]. Such shade-avoidance behavior can explain why a control patch may elongate more rapidly without recovering visual quality as quickly. Accordingly, leaf color and elongation should be treated as separate outputs in the control objective. Mechatronic lighting systems can support future precision turf management by combining light sensors, programmable LED drivers, and scheduled or rule-based control. A practical next step is to test whether canopy color, elongation, PPFD, temperature, and soil moisture can be used to adjust LED intensity and operating duration while limiting energy consumption. The present study provides the experimental and statistical evidence needed to define those future control requirements, but it does not evaluate an automated controller.

### 2.1 Light Requirements and Shade Response of Turfgrass

Shade is a major environmental constraint for turfgrass because it can reduce photosynthetic carbon gain and alter chlorophyll status, leaf morphology, biomass allocation, and root development [1]. In tropical turfgrass comparisons, Axonopus compressus showed increased relative leaf extension under simulated shade, while high shade reduced quality indicators such as green cover [2]. These findings support evaluating greenness and elongation as separate recovery outcomes. Studies of other turfgrass species likewise show that shade responses are species- and cultivar-dependent, so results from controlled-environment crops should not be transferred directly to urban turf [7], [8].

### 2.2 Supplemental LED Lighting for Turfgrass Recovery

Supplemental LED lighting can provide a controllable photon source when natural light is inadequate. In perennial ryegrass, light intensity and spectral composition affected foliar pigments, photosynthetic responses, biomass, water use, and energy consumption; an R80:B20 treatment provided a reported compromise between physiological performance and energy demand [3]. More recent turfgrass work also reports recovery-related benefits from LED supplementation under shade, but responses depend on species, intensity, spectral distribution, and exposure duration [4]. The present experiment extends this area to Axonopus compressus, while recognizing that its lamp specification was reported in lumens rather than PPFD. Comparable stadium-turf trials likewise report that LED and high-pressure-sodium supplementation can improve turf quality, density, and wear tolerance under shaded, semi-enclosed conditions, supporting the relevance of controllable supplemental lighting for stadium venues such as the present study site [9]. Mechatronic lighting systems can support future precision turf management by combining light sensors, programmable LED drivers, and scheduled or rule-based control. A practical next step is to test whether canopy color, elongation, PPFD, temperature, and soil moisture can be used to adjust LED intensity and operating duration while limiting energy consumption. The present study provides the experimental and statistical evidence needed to define those future control requirements, but it does not evaluate an automated controller.

## 3. Methodology

### 3.1 Experimental Setup

This section outlines the experimental design and quantitative analytical framework employed to evaluate the growth performance of cow grass (Axonopus compressus) under supplemental LED lighting. The study focuses on a comparative analysis of morphological parameters and physiological recovery to determine the efficacy of artificial light in enhancing turf quality.

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**Figure 1.** Experimental Design and Setup

The experiment was conducted using a controlled comparative framework consisting of two distinct treatment groups: Patch A (LED Treatment) and Patch B (Control). Both patches were established using yellowish cow grass that had been previously deprived of adequate sunlight to simulate recovery conditions.

Table 1. Lighting and Environmental Conditions of Experimental Patches

| Feature | Patch A (LED Treatment) | Patch B (Control) |
|---|---|---|
| Primary Light Source | Natural Sunlight | Natural Sunlight |
| Supplemental Light | Red/Blue LED Grow Light (5000 ± 1000 lumens) | None |
| Duration of LED Use | 7:00 PM – 10:00 PM (3 hours/night) | N/A |
| Baseline State | Yellowish (Leaf Color Score 1-2) | Yellowish (Leaf Color Score 1-2) |
| Sample Size | n = 5 specific areas per patch | n = 5 specific areas per patch |

Environmental variables, including soil composition, irrigation frequency, and daytime sunlight exposure, were kept uniform across both groups to ensure that observed differences could be attributed to the supplemental lighting. To improve measurement consistency, observations were collected at the same time of day and, where possible, from the same marked sampling locations within each patch. Leaf color was scored using the same 1–10 ordinal scale throughout the experiment, while dimensional traits were measured in millimeters using the available ruler or digital-caliper method. The source records do not specify the instrument model, measurement resolution, observer identity, lamp-to-canopy distance, LED installation height, red and blue peak wavelengths, PPFD, daily temperature, relative humidity, or irrigation volume. These details must be added by the authors from the original field log before submission; they should not be inferred from the present manuscript. The available design information is five sampling areas per patch, measurements on Days 1, 4, 9, and 15, nocturnal LED operation from 7:00 p.m. to 10:00 p.m., uniform daytime exposure, and the same stated soil and irrigation conditions for both patches.

### 3.2 Quantitative Growth Parameters

To assess the growth and recovery of the grass, six primary quantitative parameters were measured over a 15-day observation period. These parameters were categorized into physiological recovery, structural development, and turf density.

#### 3.2.1 Physiological Recovery (Leaf Color)

Leaf color was quantified using a standardized ordinal scale ranging from 1 to 10, where a score of 1 represented light green/yellow (chlorotic state) and a score of 10 represented dark green (optimal health). This metric served as a proxy for chlorophyll restoration and overall plant vitality.

#### 3.2.2 Morphological and Structural Development

Physical growth was monitored through precise measurements (in millimeters) of the following structures:

a) Leaf Length: Measured from the base of the leaf to the tip to indicate vertical elongation.
b) Leaf Width: Measured at the widest point of the leaf blade to represent lateral expansion and robustness.
c) Root/Stem Length: Measured to assess the development of the subterranean and near-ground structural components.

Stem Width: Measured to indicate the structural strength and stability of the plant.

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### 3.2.3 Turf Density (Leaf Count)

The number of leaves per branch was recorded as a discrete count to evaluate the density and coverage quality of the turf under different lighting conditions.

### 3.3 Data Collection and Analytical Framework

Data collection was performed at regular intervals (Day 1, Day 4, Day 9, and Day 15) to capture the dynamics of the growth process. The following analytical methods were applied to the raw data.

#### *3.3.1 Analytical metrics and statistical methods*

The following table summarizes the metrics used to evaluate the comparative advantage of the supplemental LED treatment.

Table 2. Summary of analytical metrics and statistical methods

| Metric | Calculation Method | Objective |
|---|---|---|
| Total Growth | | Measures overall change in growth |
| Daily Growth Rate | | Determines average daily growth |
| Standard Deviation | | Measures variability in the data |
| p-value | Mann-Whitney U Test / ANOVA | Determines statistical significance of observed differences |

#### *3.3.2 Rate-of-change analysis (linear regression)*

To provide a robust assessment of growth trends, the average daily growth rate for each parameter was calculated using linear regression across all time points. This allowed for the determination of the "Recovery Rate" (units/day) and "Elongation Rate" (mm/day).

#### *3.3.3 Statistical significance testing*

Statistical analysis was conducted to evaluate differences between Patch A (LED treatment) and Patch B (control) using both parametric and non-parametric methods. Given the small sample size (n = 5) and the nature of the data, appropriate statistical tests were selected to ensure reliability of the results. The Mann–Whitney U test was applied to leaf color scores to compare the final recovery state between the two groups. This test was selected due to its suitability for ordinal data and its robustness in small sample sizes, without assuming normal distribution. A one-way Analysis of Variance (ANOVA) was used to evaluate differences in continuous growth parameters, including leaf length, leaf width, root/stem length, stem width, and leaf count. The test was conducted with a significance level of $\alpha = 0.05$ using Google Colab. The F-value was used to assess variation between groups, while the p-value determined statistical significance.

## 4. Results and Discussion

### 4.1 Physiological Analysis

The experimental data revealed distinct growth trajectories for both patches.

Table 3. Comparative Growth Performance of Patch A and Patch B

| Parameter | Patch A (LED) | Patch B (Control) | Improvement |
|---|---|---|---|
| Final Color (Day 15) | 6.0 | 5.0 | +20% |
| Color Recovery Rate | 0.352 units/day | 0.274 units/day | +28.7% |
| Vertical Growth Rate | 1.438 mm/day | 1.915 mm/day | -24.9% |

Table 3 shows that Patch A had a higher color-recovery rate than Patch B (0.352 versus 0.274 units/day), corresponding to a 28.7% improvement. Patch A also had a lower vertical-growth rate than Patch B (1.438 versus 1.915 mm/day), corresponding to a 24.9% reduction. The higher vertical growth in Patch B is consistent with a shade-avoidance response, in which plants elongate in search of light, potentially reducing compactness and structural quality.

Table 4. ANOVA results for growth parameters

| Parameter | F-value | p-value | Significance ($\alpha = 0.05$) | Conclusion |
|---|---|---|---|---|
| Leaf length | 4.33 | 0.0395 | Significant | Significant difference exists |
| Leaf width | 0.006 | 0.938 | Not significant | No significant difference |
| Root/stem length | 0.67 | 0.413 | Not significant | Similar growth response |
| Stem width | 1.59 | 0.213 | Not significant | No significant difference |
| Leaf count | 1.31 | 0.257 | Not significant | Similar density response |

Table 4 shows that leaf length was the only parameter with a statistically significant difference between the treatment groups ($p = 0.0395 < 0.05$). This result indicates that supplemental LED lighting influenced vertical growth behavior

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under the tested conditions. Because the sample size was small, the p-value should be interpreted together with the direction and magnitude of the observed effect rather than as proof of a universal response.

In contrast, leaf width, root/stem length, stem width, and leaf count produced p-values greater than 0.05. For leaf width, the result means that LED lighting did not produce measurable lateral expansion during the 15-day observation period. For root/stem length, the result suggests that the short-term response was more evident in above-ground visual recovery than in basal or below-ground development. For stem width, the experiment did not demonstrate treatment-related structural thickening. For leaf count, the treatment did not demonstrate a statistically significant increase in turf density during the study period. These non-significant findings do not prove that the treatments have no effect; they indicate only that this experiment did not detect a statistically reliable difference under the tested conditions.

For turf practitioners, these non-significant parameters carry practical meaning beyond the statistical result. The absence of a detectable change in leaf width and stem width suggests that, over a short 15-day window, supplemental LED exposure altered the visual and vertical growth response before any corresponding change in lateral robustness became measurable; managers should therefore not expect the turf to look visibly "thicker" in the short term even where colour recovery is evident. Similarly, the non-significant result for root/stem length indicates that improvements in canopy appearance during this period were not necessarily accompanied by comparable below-ground recovery, which is relevant where turf is also being assessed for wear tolerance or structural resilience rather than colour alone. The non-significant leaf-count result suggests that supplemental lighting over this timeframe should be read as a treatment for canopy colour and elongation control rather than a short-term density or coverage intervention. These distinctions matter for scheduling supplemental lighting in venues such as stadia, where colour recovery ahead of an event may be the operational priority, while density and structural recovery are more realistically assessed over longer observation periods.

These findings support the earlier observation that Patch B exhibited greater vertical elongation, which is consistent with a shade-avoidance response under relatively light-limited natural conditions. Greater elongation should not automatically be interpreted as better recovery, because rapid extension can be accompanied by weaker or less compact turf. The LED treatment therefore appears to have improved the visual recovery trajectory while moderating vertical extension, a trade-off that should be explicitly managed in future control systems.

### 4.2 Mechatronic Control Implications

The trade-off between color recovery and vertical elongation is a critical control variable. A future mechatronic system could combine a camera-based color index with PPFD, temperature, and soil-moisture measurements, then regulate LED intensity and operating time. For example, a low color score could trigger a conservative supplemental-lighting response, while excessive elongation could reduce the daily light dose or modify the spectrum. Such rules should initially be tested in a supervised controller; reinforcement learning should be introduced only after safety limits, energy penalties, and plant-response constraints have been defined.

## 5. Conclusion

Supplemental LED lighting improved the short-term visual recovery of chlorotic Axonopus compressus in the present comparison. Patch A had a color-recovery rate of 0.352 units/day versus 0.274 units/day for Patch B, a 28.7% improvement. Its vertical-growth rate was 1.438 mm/day versus 1.915 mm/day for the control, a 24.9% reduction. ANOVA identified leaf length as the only parameter with a statistically significant between-group difference ($p = 0.0395$); leaf width, root/stem length, stem width, and leaf count were not statistically significant. These non-significant findings indicate that the experiment did not detect reliable short-term differences in lateral expansion, basal or root development, structural thickening, or turf density. The results should be regarded as preliminary because the experiment used $n = 5$ sampling areas per patch, a 15-day observation period, and a lighting specification reported primarily in lumens rather than PPFD. Future work should increase replication, document the missing environmental and instrument details, record spectral and photon-flux data, and evaluate automated LED scheduling for energy-aware urban turf management.

**Acknowledgements**

The authors would like to express their sincere gratitude to Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) for its support throughout the conduct of this research. The authors also extend their appreciation to Stadium Merdeka for its assistance during the data collection process.

**Funding**

This research was supported by Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), particularly through the Sports Technology Innovation Centre (STIC), which provided funding for the study.

**Declaration of Competing Interests**

The authors declare that they have no competing interests.

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**Data Availability of Data and Materials**
The data supporting the findings of this study are not publicly available. The underlying measurements and analysis files may be obtained from the corresponding author upon reasonable request, subject to institutional and site-specific permissions.

**Ethics Statement**
This study involved turfgrass only and did not involve human participants, animals, human tissue, or personally identifiable information. Therefore, institutional approval from a human or animal research ethics committee was not required.

**Generative AI Disclosure**
Generative AI tools were used during manuscript revision to assist with language editing, the organization of reviewer responses, and document formatting. All scientific claims, numerical results, citations, and the final manuscript were reviewed and verified by the authors. Generative AI was not used to generate experimental data, perform statistical analyses, or make research decisions.

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