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LED Light Quality and Flowering Responses in Petunia and African Marigold: A Critical Narrative Review of Spectral Effects, Cultivar Variation, and Ornamental Quality Trade-offs: A Review

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Abstract

Light-emitting diode (LED) technology provides opportunities to regulate flowering and plant architecture through manipulation of spectral composition and photoperiod. However, flowering induction, flowering time, flower production, and ornamental quality represent distinct outcomes that may respond differently to lighting treatments. This critical narrative review synthesizes selected experimental studies published between 2023 and 2026 on petunia (*Petunia × hybrida*) and African marigold (*Tagetes erecta* L.). Direct spectral experiments are distinguished from contextual studies of daily light integral (DLI). In petunia 'Easy Wave Pink', blue-to-red night interruption achieved 100% flowering but resulted in later visible bud appearance and fewer flowers than long-day lighting. Other experiments demonstrated cultivar-dependent flowering acceleration under supplemental far-red radiation. In African marigold, blue light promoted earlier flowering in a tested cultivar, whereas other spectral treatments improved flower size, biomass, or biochemical characteristics. A recent marigold study also demonstrated that treatments delaying flowering can improve selected production and quality traits. Supporting evidence from petunia DLI research indicates that moderate light exposure can maintain flowering time while reducing irrigation demand, although greater DLI generally increases flower production. Collectively, these findings suggest that LED optimization should consider flowering phenology, reproductive output, plant architecture, and resource-use efficiency rather than flowering time alone. Standardized spectral reporting, multi-cultivar experiments, and integrated commercial-quality assessments are needed to develop reliable production recommendations.

Keywords

LED Lighting;
Spectral Quality;
Far-Red Radiation;
Blue Light;
Flowering Phenology;
Petunia;
African Marigold;
Daily Light Integral;
Ornamental Quality.

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1. Introduction

Light is the one environmental factor that can influence the life of a bedding plant to a greater extent. It provides the energy to keep the plant growing, it determines how tall it will grow, whether it will branch, and whether it will commence flowering. This creates the impression for the ornamental grower that a lighting plan will be evaluated twice: by its cost of operation, and by the possibility of the plants the light plan produces being sold.

LEDs have provided growers with some level of control that was never available with the older lamps. The colour of the light and its intensity, as well as the number of hours that it is provided, can be adjusted independently. The most attention has been given to red, blue, and far-red wavelengths, as the photoreceptors of the plant are sensitive to these wavelengths, and the signal is transmitted to the processes that control growth and development.

Two species are good examples of practical stakes. Large-scale growers of petunia (Petunia x hybrida) and African marigold (Tagetes erecta L.) sell them in large quantities as both potted plants and bedding plants, as well as for landscape planting, and customers select them based on when they will bloom, the number and size of the flowers, the compactness of the plant itself, and the uniform appearance of a batch on the bench.

A number of spectral observations on flowering and form are now reported in the literature on petunia [1],[2],[3]. The same has been done for African marigold, where alterations in flowering, growth, and biochemical compound synthesis have been reported [4], [5]. It is not easy to compare these results with each other, though. The studies vary in growing conditions, and they are not necessarily measuring the same things.

This makes a practical difference. A spectrum which accelerates the proportion of plants in flower does not by any means always accelerate flowering, and one which accelerates the earliest flowering may still fail to achieve success in terms of the quantity of flowers, the size of the flower, or the general fitness for the market.

This review thus aims to review the recent experimental data, to separate the influence of spectral quality and light quantity, to identify areas of response differences between cultivars, and to suggest a framework in which flowering time balances ornamental quality and production efficiency.

2.1. Design of the review

The current article is a critical narrative synthesis of a small pool of experimental literature published between 2023 and 2026. The primary focus is placed on experiments with petunia or African marigold where the spectral composition of LEDs, far-red supplementation, or spectral treatments during the photoperiod were examined. Daily light integral (DLI) studies are only accepted as background, and they have an influence on flowering and the optimal utilization of resources. The article is neither a systematic review nor a meta-analysis. No intensive and replicable search of the bibliographic databases was conducted, and the studies under discussion cannot be considered as a comprehensive view of the literature.

2.2. Classification of the evidence

There are three types of evidence. The earliest, direct flowering evidence, is provided by experiments which manipulated spectral composition and reported flowering in the species involved. The second, supporting spectral evidence, is based on experiments which investigated the LED spectra primarily for growth, morphology, physiology, biomass, or biochemical characteristics. The third, contextual evidence, is based on experiments where the amount of light or DLI was manipulated and the effects of wavelength were not isolated. Keeping these groups apart lessens the chance that an effect of photon quantity will be credited to spectrum.

2.3. Critical interpretation

The individual studies are read with consideration of the cultivar, spectral treatment, the length of lighting, flowering endpoint, morphological features measured, and any constraint limiting the extent to which the outcome of the specific study can be extended. Wherever possible, numerical results are quoted. Since the studies vary in design and in how the measurements

were made, a qualitative discussion of the results is made, and the results are not combined into statistical estimates.

Physiological and Methodological Background

3.1. Red and far-red light

The effects of red and far-red radiation on plant development involve phytochrome-related signalling pathways. An alteration in the spectral composition can transform the flowering period, the extent of stem elongation, and the overall plant habit. These reactions, however, depend on genotype and development stage, photoperiod, and the light environment around the plant. Far-red enrichment can induce flowering in petunia cultivars that are sensitive to it, but can also promote stem growth. The grower thus has a potential conflict between earlier flowering and compact growth.

3.2. Blue radiation

Photomorphogenesis is mediated by blue radiation via phototropin- and cryptochrome-mediated signalling. It has the ability to alter the structure of plants, photosynthetic features, and reproductive processes. It would be erroneous to consider blue light as a flowering promoter in general, however, because the effect will depend on the species, the cultivar, and the experimental conditions.

3.3. Distinguishing between quality and quantity of light

In its traditional understanding, photosynthetic photon flux density (PPFD) is the number of photons between 400 and 700 nm, and DLI is the sum of these photons that are received each day. This range of photosynthetically active radiation does not include the far-red spectrum of radiation. The research which introduces far-red radiation should, in this case, mention whether the treatments were equalized using conventional PPFD or using a measure that covers a broader wavelength range. Night-interruption lighting should also be distinguished from supplemental lighting provided during the day since the former may primarily be a photoperiodic signal and not just an extra dose of photons for photosynthesis.

Effects of LED Spectra in Petunia

4.1. Night-interruption lighting

Park and Jeong (2023) varied the LED spectrum when performing a four-hour night break in petunia Easy Wave Pink. Short-day, long-day, and night-interruption treatments, the last with different spectral sequences, were compared. It was found that night interruption with blue then red light resulted in 100 percent flowering, equivalent to the long-day treatment. After 62.6 days of this treatment compared to 31.0 days of long days, bud appearance was observed, and flowering per plant was 20.3 compared to 49.6. It has been found that the percentage of flowering, the time of flowering, and the number of flowers are all independent measures of reproductive performance. This is because a treatment that can induce flowering cannot be considered the best treatment based solely on that.

Also investigated photoperiodic lighting, with warm-white and red-plus-far-red LED lamps in long-day ornamental species, which included two petunia cultivars. Their effort provides additional support to the opinion that the range of the spectrum and the timing of the treatment are also relevant to the regulation of flowering [6].

4.2. Far-red radiation and differences between cultivars

In studied DLI together with supplemental far-red radiation in the production of petunia. They discovered that far-red exposure, as well as the amount of light, had an effect on flowering and growth-related characteristics. [2] experimented on five petunia cultivars at different ratios of far-red and varying levels of DLI. At low DLI, an increase in the fraction of far-red, approximately by 19 percent, accelerated flowering by approximately 20 days in the diploid variety Mitchell Diploid, but only by two days in the diploid variety Fotofinish White. The magnitude of the practical significance of the far-red effect on flowering time is consequently disparate across cultivars. However, these differences between cultivar responses cannot be regarded as an established cultivar-by-spectrum interaction unless an appropriate combined statistical test has established them. [3]

4.3. Flowering and vegetative growth

It was also reported by [3] that far-red enrichment failed to increase the shoot dry weight on a regular basis, but that DLI impacted biomass accumulation in a number of commercial cultivars. Far-red radiation also changed stem elongation. Earlier flowering, compactness, and biomass can thus react differently to the identical light treatment, and the earlier-flowering treatment may not give the most desirable plant to be sold.

4.4. Molecular evidence

In the gene expression of FLOWERING LOCUS T under low and high light conditions. These observations provide molecular evidence that accompanies the flowering responses. The modification of gene expression, in any case, cannot be recognized as evidence of causation until it is proven by functional tests [3].

4.5. Additional LED and cultivar-specific production

In their study, subjected two varieties of petunia to a series of supplemental LED lighting experiments in the greenhouse setting and compared various combinations of red and blue light with white light. The treatments influenced some physiological and productive characteristics, including the reaction of flower dry mass. The results justify the idea of evaluating individual cultivar performance and discourage the notion that a single spectral combination is more desirable than all others [7].

5. LED Spectral Effects in African Marigold

5.1. Flowering responses to blue light

In study cultivated African marigold cultivars Antigua Orange and Antigua Yellow under red, blue, white, and red-blue light. Spectral composition influenced growth and flowering as well as pigment-related traits. Plants in the yellow cultivar flowered earlier than those under white light, by approximately 19.2% in flowering time. This itself is a direct indication that blue light may accelerate reproductive development in at least one marigold cultivar. The result cannot be extended to other cultivars or production systems without further support [4].

5.2. Flower size and biomass

The same authors discovered that there were differences in flower characteristics across the spectral treatments. The flowers in Antigua Orange were approximately 4.06 cm in diameter in white light and 3.37 cm in blue light. A treatment which produces flowers earlier may not be the one which produces the largest flowers, and time to flowering cannot by itself determine ornamental quality.

5.3. Spectral mixtures and productive performance

In experimented with LED combinations on African marigold in a controlled setting. Spectral treatments affected growth, flowering, biomass production, and biochemical characteristics. A combination of white, blue, and red light slowed down flowering by up to 20 days compared with some of the other treatments, although the mixed spectra also provided good results for plant and flower production. Late flowering, in itself, is not necessarily an indicator of poor performance. The preferred spectrum would be based on the weight put on flowering time, flower yield, plant growth, and biochemical characteristics [5].

6. Comparative Discussion

6.1. Differences in experimental emphasis

Recent petunia studies have focused on far-red radiation, photoperiodic lighting, and the acceleration of flowering. African marigold studies have more commonly included broad spectral mixes and have reported a larger repertoire of morphological and biochemical phenotypes. The experiments vary in cultivars, lighting conditions, and measurement procedures and cannot demonstrate that either of the species is inherently more sensitive to a particular wavelength. To have a fair comparison between the species, standardized conditions would be required.

6.2. Flowering percentage versus flowering time

The experiment shows that the percentage of flowering plants is not enough to judge a lighting treatment. Two treatments may have an equal percentage, yet differ greatly in time to flower and the number of flowers produced. The percentage of flowering plants, days to first flower, and flower production should thus be reported in future studies as separate outcomes [1].

6.3. Flowering acceleration versus ornamental quality

Observations in both species show that there can be a cost to advancing flowering. In petunia, far-red radiation can accelerate flowering, but it also extends the stems. In African marigold, blue light can produce earlier flowering, and other spectra can produce larger flowers or more biomass. The best spectrum is therefore the one that aligns with the production purpose of the grower.

6.4. DLI and irrigation efficiency

In study compared four DLI levels: 2.8, 4.9, 6.9, and 17.4 mol m^{-2} d^{-1}. In petunia, moderate DLI produced similar flowering periods to higher DLI, and higher DLI tended to increase flower number and dry biomass. Mean irrigation demand was about 16.83 L per plant at 6.9 mol m^{-2} d^{-1} and 26.33 L at 17.4 mol m^{-2} d^{-1}. The 9.50 L difference would be equivalent to a 36.1% saving compared to the higher DLI. The percentages provided in the highlights and in the detailed abstract of the published article do not agree with each other; the figure provided here was calculated by dividing the difference between the treatment means by the treatment means. It is also worth noting that in this research there was a variation in the amount of light and not the spectrum. It demonstrates the necessity of controlling DLI in spectral experiments, but does not demonstrate any wavelength-specific irrigation effect [8].

6.5. Interpretation of the available evidence

The reviewed studies lead to three key conclusions. Spectral manipulation has the capacity to alter flowering in African marigold and petunia. Response size and direction are dependent on genotype, lighting, and the trait being measured. Furthermore, the first to flower may not always be the most ornamental or the most economical in resource utilization. All these findings combine to support lighting that is optimized to meet multiple goals simultaneously and reject the notion of a single spectral recommendation that fits all situations.

7. Research Gaps and Future Priorities

7.1. Standardized flowering endpoints

Subsequent experiments should document independently the days to visible bud, days to first open flower, days to full flowering, the percentage of plants in flower, and the total number of flowers.

7.2. Standardized spectral measurements

The entire spectral distribution of each treatment should be provided along with PPFD, DLI, photoperiod, and the quantity of far-red radiation received by the plants.

7.3. Multiple cultivars

There should be more than one cultivar in experiments, so that responses which are genotype-dependent can be observed. The interaction of cultivar and spectrum is to be determined by a statistical test and not simply by comparing treatments cultivar by cultivar.

7.4. Commercial ornamental quality

The number of flowers, flower diameter, flower biomass, plant height, branching, compactness, and overall appearance of the plant as a sellable product should be evaluated simultaneously in studies.

7.5. Resource-use efficiency

The lighting should be evaluated considering how much electricity is used, how much water is used in irrigation, the production cycle duration, and how many products can be sold.

7.6. Experimental replication

The lighting treatments must be independently replicated at the level of the actual experimental unit. The effect of the chamber should be designed into and analyzed when growth chambers are used or when separate lighting compartments are used, or the effect of the chamber will be pseudo replicated.

8. Proposed Multi-Objective Research Framework

The red-blue combinations (with and without the addition of far-red radiation) should be compared in the future, and DLI and photoperiod should be maintained constant. A number of cultivars of petunia and African marigold ought to be included. Primary responses that will be quantified include flowering time, flower quantity, plant structure, and resource utilization efficiency. The design should be appropriate, and a factorial analysis or a mixed-effects model must be selected, and the interactions between cultivar, spectrum, and DLI must be analyzed. Effect sizes and confidence intervals should be provided with tests of significance. Such a multi-objective strategy would subsequently be able to identify those lighting treatments that make a trade-off between flowering time, ornamental quality, and resource economy. Pareto-front analysis is better than allocating arbitrary numbers to the objectives where no justifiable method of weighting them exists.

9. Conclusions

LED spectral composition influences flowering and development in petunia and African marigold, but the nature of the response varies depending on the cultivar, the lighting environment, and the trait of interest.

Spectral treatments administered to petunia as night interruptions can alter flowering. Flowering plants may also show substantial differences in the time to flower and the number of flowers even though they have the same flowering percentage. In flowering cultivars that are responsive, supplemental far-red radiation can accelerate flowering, but can increase stem length.

Under some conditions, blue light can induce flowering in African marigold, and other spectra can produce larger flowers, higher biomass, or better biochemical properties.

The available evidence is not yet sufficient to justify the suggestion of an optimal LED spectrum for the two species.

The uniform measurement of the spectrum, control of DLI, application of multiple cultivars, independent replication, and an integrated measure of flowering, ornamental quality, and resource efficiency should therefore be given priority in future studies. Such work would provide a more solid base for lighting strategies that are commercially viable and adapted to the specific cultivar.

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