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Article

Lighting the way to profitable cut-flower production: a comparative study of HPS and LED lamps in *Aster* sp. and *Solidago canadensis*

Iluminando o caminho para a produção lucrativa de flores de corte: um estudo comparativo de lâmpadas HPS e LED em *Aster* sp. e *Solidago canadenses*

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Abstract: Light supplementation with HPS lamps is widely used in the production of short-day cut-flowers, such as *Aster* sp. and *Solidago canadensis*; In turn, LEDs are an affordable energy-saving alternative to replace HPS lamps, but its effectiveness in *Aster* sp. and *S. canadensis* was not studied yet. Thus, the aim of this study was to evaluate the influence of HPS and LED lamps on growth, development, flowering inhibition, and profitable value of *Aster* sp. and *S. canadensis*. For this, two assays with five hours of light supplementation were conducted, each one corresponding to one species. *Aster* sp. varieties were: Annency, Cirina, and White; light sources: HPS or LED lamps; and light intensities: intense or diffuse. The phenological development was not affected by light sources or intensities, with all treatments effectively inhibiting premature flowering in both species. Stem length was reduced under LED lamps in *A.* White, while the other growth parameters were unaffected or improved in the other varieties and species. The fewer "carnival" stems (exportation market) under LED lamps had a lower income; however, LEDs resulted in higher profits due to its lower energy consumption (47.35% lower than HPS). Therefore, LED lighting effectively inhibited premature flowering in *Aster* sp. and *S. canadensis* and maintained the quality of the cut-flowers at a lower production cost.
Keywords: cost-benefit, phenology, high-pressure sodium lamp, light-emitting diodes, photoperiod.

Resumo: A suplementação de luz com lâmpadas HPS é amplamente utilizada na produção de flores de corte de dia curto, como *Aster* sp. e *Solidago canadensis*; por sua vez, os LEDs são uma alternativa econômica e acessível para substituir as lâmpadas HPS, mas sua eficácia em *Aster* sp. e *S. canadensis* ainda não foi estudada. Assim, o objetivo deste estudo foi avaliar a influência das lâmpadas HPS e LED no crescimento, desenvolvimento, inibição da floração e valor lucrativo de *Aster* sp. e *S. canadensis*. Para isso, foram conduzidos dois ensaios com cinco horas de suplementação de luz, cada um correspondendo a uma espécie. As variedades de *Aster* sp. foram: Annency, Cirina e White; fontes de luz: lâmpadas HPS ou LED; e intensidades de luz: intensa ou difusa. O desenvolvimento fenológico não foi afetado por fontes ou intensidades de luz, com todos os tratamentos inibindo efetivamente a floração prematura em ambas as espécies. O comprimento do caule foi reduzido sob lâmpadas LED em *A*ster White, enquanto os outros parâmetros de crescimento não foram afetados ou melhoraram nas outras variedades e espécies. Na variedade "Carnival" (destinada ao mercado de exportação), a menor quantidade de caules produzidos sob LEDs resultou em uma redução na receita. No entanto, o uso de LEDs proporcionou maior lucratividade devido ao menor consumo de energia, que foi 47,35% inferior ao das lâmpadas HPS. Portanto, a iluminação LED inibiu efetivamente a floração prematura em *Aster* sp. e *S. canadensis* e manteve a qualidade das flores de corte a um menor custo de produção.
Palavras-chave: custo-benefício, diodos emissores de luz, fenologia, fotoperíodo, lâmpada de sódio de alta pressão.

Introduction

Light is essential for plant growth and development, as it is the driven force for photosynthesis and the inducing signal for several developmental process (de Wit et al., 2016). Ligh quality (color/wavelength), quantity (intensity), and duration (photoperiod) strongly affect plant growth and development and, as such, can be altered to reach higher crop yields (Pereira et al., 2021). In this context, the use of artificial light technologies has evolved as an alternative for plant cultivation allowing a higher control of developmental phases and crop production (Chiang et al., 2020). For instance, under greenhouse and growth chambers (e.g., for nursery or vertical farming) conditions, light is a key parameter, and fine control of light quantity (intensity and duration) and quality (wavelength composition) is a challenge to increase the yield and value of products (Paradiso and Proietti, 2022). In addition to higher crop yield, the adequate use of artificial lighting can also reduce energy costs and minimize their environmental impacts (Lan et al., 2022; Trivellini et al., 2023).

For floriculture production, the use of artificial light in some crops is essential to prevent or promote flowering, allowing for a harvesting schedule according to the market demands (Proietti et al., 2022). Prolonged photoperiod through light supplementation is imperative for short-day species (SDS) production, as it favors vegetative growth and prevents premature flowering, floral abortion, and flower malformation, which reduce cut flower quality (Spall and Lopez, 2022). This is the case of equatorial countries such as Ecuador, where there is no seasonal variation in day length (Borchert et al., 2005), making it necessary to use light supplementation. For instance, cultivation of the SDS *Aster* sp. and *Solidago canadensis* on Ecuador require supplementary light to prevent premature flowering induction. *Aster* sp. is a perennial flowering herb belonging to the Compositae family; its capitulum flowers, that can be blue, purple, violet, pink or white, are widely used in gardens and cut-flower market (Oren-Shamir et al., 2000). In turn, *S. canadensis*, also known as Canada goldenrod, is a perennial herb belonging to the Asteraceae family and native from North America, which produces attractive yellow flowers that are used as cut-flowers worldwide (Qiang et al., 2021; Collaguazo-Lita et al., 2022).

Among the lamps used for light supplementation, high-intensity discharge (HID) lamps, such as metal halide (MH) and high-pressure sodium lamps (HPS), are typically used in greenhouses and plant growth chambers (Nelson and Bugbee, 2014). However, these lamps represent a significant portion of companies' budgets due to their energy consumption

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(Katzin et al., 2021). Thus, new technologies have promoted the use of light-emitting diodes (LEDs), which provide comparable effectiveness to conventional light sources, featuring a long life, low energy consumption, small mass and volume, low radiant heat output, and the ability to emit specific spectral qualities, lowering total operating costs (Craver et al., 2022; Katzin et al., 2021).

Despite the promising results of the use of LEDs in light supplementation, the use of new technologies requires validation to be effectively implemented, as plant responses to light are species- and cultivar-dependent (Ouzounis et al., 2015; Rouphael et al., 2021). Moreover, the effectiveness of LEDs in delaying premature flowering in *Aster* sp. and *S. canadensis*, as well as its cost-benefit compared to HPS lamps, was not assessed yet. Beyond the direct benefits for floriculture, this study is significant in the broader context of innovation and technology applied to agricultural sciences. The integration of energy-efficient LED technology with precise light management represents a step forward in sustainable crop production, reducing environmental impacts while optimizing yield and quality. By bridging scientific knowledge with technological advancements, our findings contribute to the modernization of floriculture, fostering more resource-efficient and economically viable production systems.

Thus, the aim of this study was to evaluate the influence of HPS and LED lamps on growth, development, flowering inhibition, and profitable value of *Aster* sp. and *S. canadensis*. The hypothesis is that LED lamps can effectively inhibit premature flowering in these species while maintaining or improving growth and quality parameters compared to HPS lamps, offering a more energy-efficient and cost-effective alternative for light supplementation in short-day cut-flower production.

Material and methods

Experimental description

Two independent assays were conducted to assess the influence of light quality and quantity on *Aster* sp. and *S. canadensis*, each assay corresponding to one species. The experiment was conducted in a greenhouse with a total area of 320 m^2. The seedlings (Flores del Valle S.A., Quito, Ecuador) were planted at 15 cm between plants and 15 cm between rows. Plants were pinched (35 - 40 cm of upper stem) between the fifth and sixth week (Dole and Wilkins, 2004; Yumbla-Orbes et al., 2020). The phytosanitary control and weeding management were performed according to the crop needs. The fertigation was provided through an automated drip irrigation, three times a day, for seven minutes. The first irrigation consisted of acidified water with phosphoric acid; while for the second and third irrigations, the fertilizers corresponded to potassium nitrate, calcium nitrate, ammonium nitrate, potassium sulfate, magnesium sulfate, monoammonium phosphate and micronutrients, following the proportion used for the flower farm.

The effect of light quality on *Aster* sp. production was studied in an experiment arranged in a completely randomized blocks design, in a 3 × 2 factorial scheme (three *Aster* sp. varieties × two light sources), with five repetitions, and ten stems corresponding to the experimental unit. The three *Aster* varieties used were Annency (purple), Cirina (pink), and White; and the light sources used were HPS lamps (peak at 600 nm – yellow) or LED lamps (peak at 660 nm – red) (Fig. 1).

On the other hand, the effect of light quality and intensity on *S. canadensis* was evaluated in an experiment arranged in a completely randomized blocks design, in a 2 × 2 factorial scheme (two light sources × two light intensities), with five repetitions, and ten stems corresponding to the experimental unit. The light sources used were HPS lamps (peak at 600 nm – yellow) or LED lamps (peak at 660 nm – red), at two intensities: intense or diffuse. For HPS lamps, intense and diffuse light corresponded to 6.84 $\mu mol\ m^{-2}\ s^{-1}$ and 3.53 $\mu mol\ m^{-2}\ s^{-1}$, while for LED lamps, intense and diffuse light corresponded to 1.64 $\mu mol\ m^{-2}\ s^{-1}$ and 0.21 $\mu mol\ m^{-2}\ s^{-1}$ (Fig. 1d).

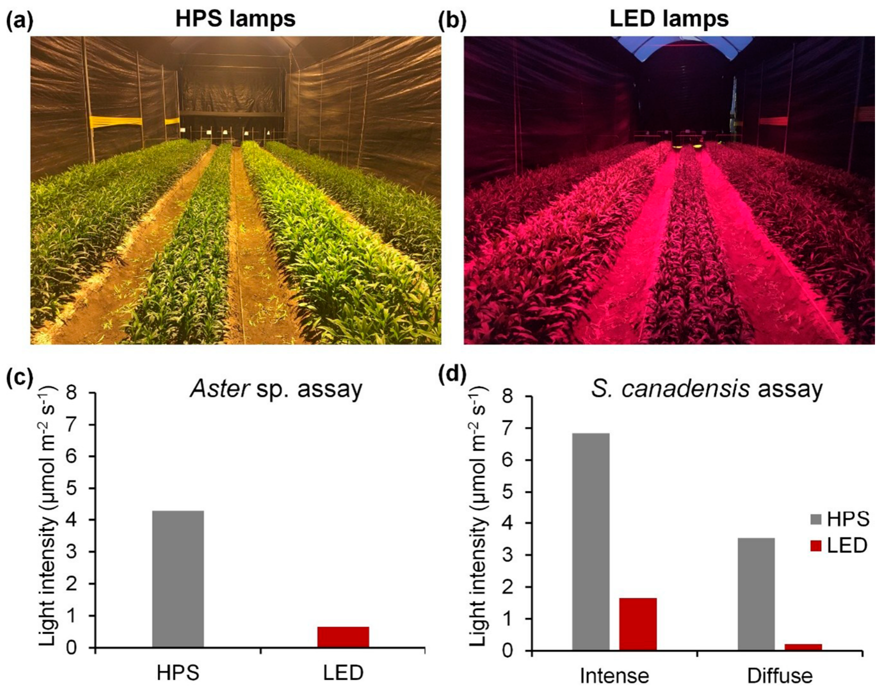

Fig. 1. Pictures of the greenhouse units using HPS (yellow) or LED (red) lamps for light supplementation (a and b). Light intensity measured under each condition evaluated in this study (c and d).

The HPS treatment comprised three lamps (400 and 2 x 250 W, totaling 900 W), and the LED comprised three lamps (150 W, totaling 450 W). The irradiance at the plant canopy was measured in four points per block, using a full-spectrum meter (Daily Light Integral, and Photoperiod Meter (Full-Spectrum, 400-700 nm) Model: DLI-500: PAR, Apogee Instruments). The cultivation ambient and its characteristics can be seen in Fig. 1. Artificial lighting was maintained constant from 6:30 a.m. to 11:30 p.m. (17 h light/7 h dark photoperiod), starting at transplantation and lasting until the eighth week of cultivation. Each greenhouse unit, corresponding to one light treatment, was completely isolated from external light sources by using black plastic films.

Evaluations

Phenological stages were determined every ten days, starting after the first week of establishment until harvest. Phenological identification was performed based on the scale developed by

Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) for weeds (Bleiholder et al., 1998; Meier et al., 2009), since *S. canadensis* and *Aster* sp. are considered as weeds in its country of origin. The percentage of induced plants corresponded to the number of plants showing premature flowering, even with light supplementation, in relation to the total number of plants of each block.

Flowers were harvested when plants presented 30% to 40% of open flowers in inflorescences, and the days to harvest, number of branches per plant, stem diameter, and stem length were determined. Moreover, after harvest, plants were separated by treatments (900 plants in total) and classified according to their size: > 75 cm length – exportation market ("carnival stems"); or < 65 cm in length – domestic market ("normal stems"). The costs and profits of each light source per ha were estimated considering the costs with energy consumption (0.087 USD per kWh) and the sale price (USD) for carnival (U$ 0.10/plant for *Aster* sp., and U$ 0.05/plant for *S. canadensis*) and normal stems (U$ 0.16/plant for *Aster* sp., and U$ 0.08/plant for *S. canadensis*). The calculations were based on the currency values for the 2021/2022 season.

Statistical analysis

Data were tested for normality and homogeneity, and then subjected to analysis of variance (ANOVA; F test). The means of the significant variables were compared by Tukey's test ($p \leq 0.05$) using the Genes software (Cruz, 2016).

Results

No differences among the three *Aster* varieties and in *S. canadensis* in response to the evaluated light conditions were found for most of the phenological stages determined by the BBCH scale. The only differences for *Aster* sp. occurred at 10 and 30 days after transplant (DAT), when *A*. Cirina presented fewer leaves and basal sprouts, respectively, independently of the light condition. On the other hand, no differences were found for *S. canadensis* in response to light quality and quantity.

Effects of light quality on Aster sp.

Both Annency and Cirina showed lower plant induction when using LED (note that even in Annency the reduction is approximately 25% - 30%), but, statistically, only Cirina showed a difference in relation to the type of lamps (Fig. 2a).

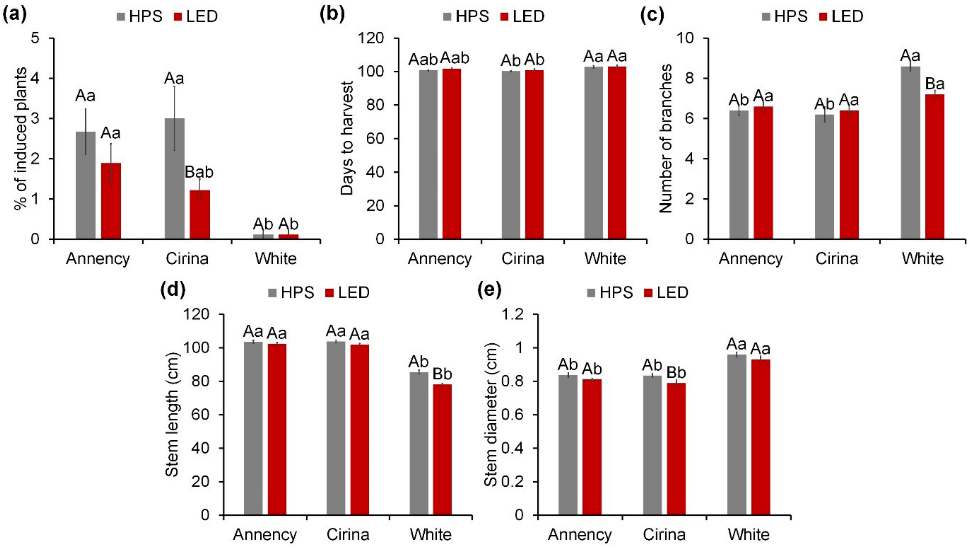

Fig. 2. Percentage of induced plants, days to harvest, and morphometry of three varieties of *Aster* sp. grown under light supplementation with high pressure sodium vapor lamps (HPS) or light emitting diodes (LED). Bars represent the mean ± standard error. Capital letters compare HPS with LED within each *Aster* variety, and lowercase letters compare varieties within each light source through Tukey's test ($p \leq 0.05$).

The *A*. White variety took more days to be harvested compared to *A*. Cirina, that had the fewer days to harvest, while the light source did not alter this variable (Fig. 2b). Moreover, *A*. White had higher number of branches under HPS lamps than under LED lamps, while no difference was found for the other varieties, that showed fewer branches that *A*. White under HPS lamps (Fig. 2c). *A*. White also had the lowest stem length and the highest stem diameter compared to *A*. Annency and Cirina, under both light sources (Fig. 2d, Fig. 2e). In addition, compared to the use of HPS, LED lamps resulted in lower stem length in *A*. White plants, and in lower stem diameter in *A*. Cirina plants (Fig. 2d, Fig. 2e).

According to the analysis of production costs per cycle, the HPS treatment had a final cost of 6477.03 USD per ha and the LED 3067.16 USD per ha, with the HPS treatment being 47.35% more expensive (Table 1).

Table 1. Profits and losses generated by lighting source per ha during one production cycle of *Aster* sp. LS: Light source; CS: Carnival stems per ha; NS: Normal stems per ha; S: Sales (USD); SLS: Sales per light source (USD); EC: Energy consumption (USD); P: Profit per ha (USD).

<table>
<tr><th>Aster var.</th><th>LS</th><th>CS</th><th>NS</th><th>S</th><th>SLS</th><th>EC</th><th>P</th></tr>
<tr><td>Annency</td><td>HPS</td><td>48622.27</td><td>3042.48</td><td>5014.35</td><td rowspan="3">15080.37</td><td rowspan="3">6477.04</td><td rowspan="3">8603.33</td></tr>
<tr><td>Cirina</td><td>HPS</td><td>50918.48</td><td>746.27</td><td>5129.16</td></tr>
<tr><td>White</td><td>HPS</td><td>47072.33</td><td>4592.42</td><td>4936.85</td></tr>
<tr><td>Annency</td><td>LED</td><td>46670.49</td><td>4994.26</td><td>4916.76</td><td rowspan="3">14836.39</td><td rowspan="3">3067.16</td><td rowspan="3">11769.23</td></tr>
<tr><td>Cirina</td><td>LED</td><td>50287.03</td><td>1377.73</td><td>5097.59</td></tr>
<tr><td>White</td><td>LED</td><td>44776.12</td><td>6888.63</td><td>4822.04</td></tr>
</table>

The use of LED lamps reduced the quality of *Aster* cut-flowers, as shown by the shorter stems, which resulted in an income 243.98 USD lower than under HPS lamps; however, as the cost of energy consumption of LED lamps is 3409,88 USD cheaper than HPS lamps, LED lamps resulted in profits 3165.90 USD higher than HPS lamps.

Effects of light quality and quantity on *S. canadensis.*

No differences among light qualities (HPS and LED lamps) were found for the percentage of induced plants, days to harvest, and stem length (Fig. 3a, 3d). In turn, intense LED lamps resulted in lower number of branches, and diffuse LED resulted in lower stem diameter compared to HPS lamps (Fig. 3 c, 3e). On the other hand, light quantity strongly affected the percentage of induced plants, with intense light resulting in more prematurely induced plants than diffuse light, under both light sources (HPS and LED) (Fig. 3a).

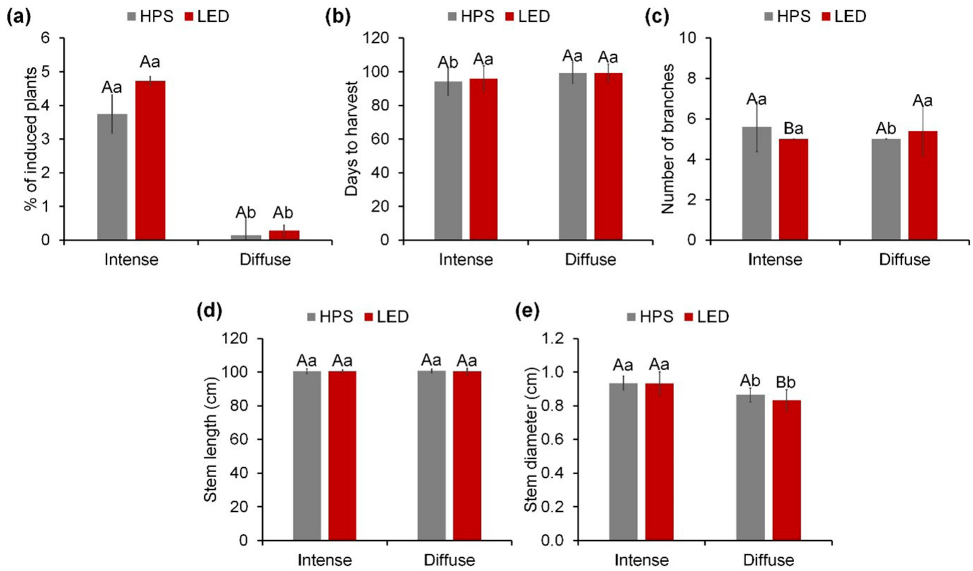

Fig. 3 Percentage of induced plants, days to harvest, and morphometry of *Solidago canadensis* grown under light supplementation with high pressure sodium vapor lamps (HPS) or light emitting diodes (LED) at two irradiance levels (intense or diffuse). Bars represent the mean ± standard error. Capital letters compare HPS with LED within each irradiance level, and lowercase letters compare irradiance levels within each light source through Tukey's test ($p \leq 0.05$)

Diffuse light, provided by HPS lamps, also reduced the number of branches compared to intense light (Fig. 3e). Moreover, diffuse light resulted in lower stem diameter compared to intense light under both light sources (Fig. 3e). No differences among light sources and quantities were found for stem length (Fig. 3d).

The income generated by the lighting sources in *S. canadensis* was similar, however, due to the energy costs, the LED source reached greater profits than HPS lamps (Table 2). In addition, the diffuse LED treatment had a slightly higher income than the diffuse HPS, while the income under intense LED was slightly lower than under intense HPS.

Table 2. Profits and losses generated by lighting sources and irradiance levels per ha during one production cycle of *S. canadensis*. LS: Light source; IL: Irradiance level; CS: Carnival stems per ha; NS: Normal stems per ha; S: Sales (USD); SLS: Sales per light source (USD); EC: Energy consumption (USD); P: Profit per ha (USD).

LS	IL	CS	NS	S	SLS	EC	P
HPS	Intense	48163.03	3501.72	7986.22	15582.09	6477.04	9105.05
HPS	Diffuse	43283.58	8381.17	7595.87			
LED	Intense	47187.14	4477.61	7908.15	15586.68	3067.16	12519.52
LED	Diffuse	44316.88	7347.88	7678.53			

Discussion

The lighting sources and intensities did not affect the development of *Aster* sp. and *S. canadensis* any phenological phase, as shown by the lack of differences on phenological development based on the BBCH scale. Similar results were found for the SDS *Chrysanthemun morpholium*, where no differences in phenological phases was observed between light supplementation with red (660 nm) or yellow (570 nm) LED lamps (Mah et al., 2021).

Although *Aster* plants are SDS, requiring short-days to flowering, they may eventually show a low flowering induction even under long days (Farina et al., 1994). Premature flowering inhibition of SDS under inducible conditions (short-days) is imperative to produce high quality cut-flowers (Spall and Lopez, 2022). Here, the artificially extended photoperiod through both light sources (LED and HPS lamps) effectively prevented the premature flowering of the three varieties of *Aster* sp. and of *S. canadensis*, as shown by the low percentage of induced plants (below 5%). In addition, a variety-specific response to LED lighting was observed in *Aster* sp., as *A*. Cirina had fewer induced plants under LED compared to HPS lamps, but no difference was found for the other varieties. On the other hand, *A*. White plants flowering was more effectively inhibited independently of the light source, being more responsive to the light supplementation. The differences in *Aster* varieties responses to photoperiod were previously reported (Farina et al., 1994). Interestingly, on *S. canadensis*, light quality did not influence premature flowering; however, it was altered by light intensity, as diffuse HPS and LED light resulted in fewer prematurely induced plants, being more effective than intense lighting.

In addition to the flower inhibition through the extended photoperiod, low irradiance, followed by low red: far red ratios, can also affect other aspects of plant development, such as leaf expansion, petiole elongation (etiolation), accelerated flowering, and lower branching (de Wit et al., 2016). In fact, we found differences in the number of branches and stem length and diameter in response to the light sources and intensities. In *Aster* sp., these effects were variety-specific, with *A*. White showing the latest harvest, the highest stem diameter and the lowest stem length under both light sources, with stem length and branching being reduced under LED lighting; this suggests a higher induction of shade avoidance responses in *A*. Annency and Cirina than in *A*. White under the evaluated conditions. Similarly, in *S. canadensis*, the earlier harvest and the lower branching under low light intensity with diffuse HPS, as well as the lower stem diameter under diffuse HPS and LED also suggest that low light resulted in some extent of shade responses. Nonetheless, these morphological alterations did not impair the production of *Aster* sp. and *S. canadensis*, as the harvest occurred around 90 to 110 DAT, that is the desirable harvest time (Sakata, 2023). It is noteworthy that all the treatments reached the required quality parameters established by the market (> 75 cm length for exportation market, and < 65 cm in length for domestic market) (ValleFlor, 2020). Moreover, the fact that *A*. Cirina and Annency presented longer stems (≥ 100 cm) suggests that the number of days of complementary lighting can be reduced in these varieties, shortening the productive cycle and decreasing production costs.

The traditional artificial lighting by HPS lamps produce a lot of heat (infrared radiation), which accounts for 25% of the electrical energy input (Nelson and Bugbee, 2014). Thus, the use of LED lamps is a well-stablished energy-saving solution in replacement of these traditional lamps in artificial lighting of controlled environmental conditions, substantially reducing production costs (Craver et al., 2022; Katzin et al., 2021). However, it is important to acknowledge certain limitations of our study. While our results demonstrate the benefits of LED lighting in terms of energy efficiency and premature flowering inhibition, the study was conducted under controlled conditions that may not fully reflect the variability encountered in commercial production systems. Factors such as seasonal fluctuations, environmental interactions, and potential cultivar-specific responses in different geographical regions should be further explored to validate the broad applicability of our findings. Additionally, a longer-term assessment of economic viability, considering potential variations in light efficiency over time, would strengthen the practical recommendations derived from this study.

Here, despite LED lamps slightly reduced the production of carnival stems, resulting in a lower income, after consider the production costs of each light source, LED lamps resulted in a more profitable production of *Aster* and *S. canadensis* cut-flowers. In a broader perspective, this study highlights the role of innovation and technology in advancing sustainable agricultural practices. The integration of energy-efficient LED lighting with precise photoperiod control exemplifies how scientific advancements can lead to practical solutions that optimize production while reducing environmental and economic costs. By bridging fundamental plant physiology with technological innovation, our findings contribute to the modernization of floriculture, promoting more efficient and resource-conscious cultivation strategies.

Conclusions

The extended photoperiod through both artificial light sources (LED and HPS) effectively prevents the premature flowering of the three varieties of *Aster* sp. and of *S. canadensis*. HPS lamps resulted in longer stems compared to LED lamps, resulting in higher income; however, due to its lower energy consumption, LED lamps resulted in a more profitable production of *Aster* sp. and of *S. canadensis*.

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Author Contribution

JACC: Conceptualization, Formal Analysis, Writing – Original Draft. **JMH:** Visualization, Writing – Review & Editing. **DSB:** Visualization, Writing – Review & Editing. **CVPP:** Formal Analysis, Writing – Original Draft**. MYO**: Formal Analysis, Supervision, Resources, Writing – Original Draft.

Conflict of interest

There are no conflicts of interest to declare.

Data Availability Statement

All the research data is contained in the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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