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RESEARCH ARTICLE
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Effect of Different Types of Led Lighting on Growth Parameters and Productivity of Greenhouse Tomato

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ABSTRACT

This study compared two locally engineered LED irradiators (KSDO-1 and KSDO-2) for their efficiency in accelerating growth and productivity of greenhouse tomato (*Solanum lycopersicum* L.). The work was motivated by the need for energy-saving, crop-specific lighting to enable year-round tomato production in northern Kazakhstan. Experiments were conducted at the LedSystemMedia greenhouse complex (Astana, Kazakhstan) using the F1 hybrid 'Forticia RC' grown hydroponically. Plants were illuminated with either high-pressure sodium (HPS; control) or one of the two LED treatments. Main physiological and morphological parameters, such as plant height, internode length and leaf area. Quantum yield of photosystem II (Y(II)) and fruit productivity were measured during the vegetative and reproductive periods. The biochemical content of the fruits was also determined. Measurements were made according to standard national methods and with the help of specialized equipment (MINI-PAM-II fluorometer). Tomato plants subjected to LED treatments. Particularly, KSDO-2 showed significantly better performance. The total yield was enhanced by 150.2% (KSDO-1) and 152.6% (KSDO-2) compared to the control. Increased photosynthetic efficiency shortened internodes, increased leaf area (by 20–24%), and extended fruiting periods were found under LED illumination. No differences were noticed in fruit biochemical quality among the treatments. The results indicate that LED irradiators designed according to plant photosynthetic requirements have the potential to significantly increase tomato production in controlled environments. The KSDO-2 model proved to be the most efficient and is now being prepared for patenting, being a promising development in energy-saving greenhouse lighting technology.

Keywords: Greenhouse, Tomato, LED lighting, Productivity, Biological parameters

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INTRODUCTION

The drive to increase productivity in the agricultural sector has led to the intensive use of fertilizers and pesticides under conventional farming practices. Consequently, the search for new and more efficient cultivation methods has become a priority, driving the rapid development of hydroponics in recent years (Filho, 2009; Bunning & Kendall, 2012; Kussainova et al., 2018). The growth and development of greenhouse plants directly depend on key environmental factors, with light being one of the most crucial. In greenhouses, the required amount of light is provided through natural sunlight during the summer and supplemental lighting during the winter season. Light within the photosynthetically active radiation (PAR) range drives photosynthesis, of which plants absorb roughly 80–90%. Photosynthetic efficiency peaks in the blue and red regions of the spectrum. Blue light typically produces smaller but thicker leaves and stimulates chlorophyll biosynthesis, whereas red light promotes flowering and fruit set (Tsydendambaev, 2008).

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To achieve optimal yields in both quantitative and qualitative terms, the intensity spectral composition and duration of light exposure must be adapted to the needs of the plant (Dorais et al., 1996). Selecting the appropriate spectrum and radiation of LED lighting (LEDs) requires analysis of the effects of different lamp types on plant growth and development. Including the optimization of structural and technological parameters of the lighting system (Martirosyan et al., 2008). Modern LEDs for greenhouse use consume three times less energy while maintaining similar light output. They also provide an ideal light spectrum that does not cause plant overheating and contain no harmful substances or additives in their production (Dannehl et al., 2021). In greenhouse vegetable cultivation, the total PAR in December–January varies significantly across different climatic zones. In Zone IV (Akmola Region), it is 1000–1380kcal/cm². While in Zone VI (Almaty Region), it reaches 1770–2280kcal/cm². These levels are insufficient for growing vegetable crops during this period in all light zones of the Republic of Kazakhstan. As a result, greenhouse production is considered one of the most energy-intensive sectors. In recent years, there has been a global shortage of electricity, making the modernization of greenhouse systems by replacing traditional sodium lamps with LEDs a timely and necessary solution.

The most energy-efficient sources for cultivating plants in protected environments are currently based on LED lighting systems. As electricity prices continue to rise, upgrading greenhouse infrastructure and replacing traditional light sources with LED fixtures is becoming increasingly relevant (Tamulaitis et al., 2005; Kitao et al., 2013; Ying et al., 2020). The global shift toward energy conservation and efficiency, reinforced by international agreements such as the Paris Climate Accord, underscores the urgent need to transition to clean energy sources in the face of rising electricity demand and periodic shortages. In this context, the use of new efficient LED lighting systems in the construction or modernization of greenhouses is of great importance. Energy costs include both thermal and electrical energy, and account for more than 60% of the production cost in industrial greenhouse vegetable cultivation (Karimov, 2017). It is known that high-pressure sodium (HPS) arc tube lamps account for 35–40% of the lighting used in greenhouse vegetable production. At the same time, the efficiency (useful output ratio) of HPS lamps is approximately 70% with the remaining energy dissipated as heat. In contrast, over 80% of the energy consumed by LEDs is converted directly into light. To date, a considerable body of evidence supports the high efficiency of using LED-based lighting for vegetable cultivation under controlled conditions (Avercheva et al., 2009; Van Santen, 2013; Sytnikov, 2013) as well as the impact of light with different spectral compositions on plant productivity (Protasova et al., 1990; Tikhomirov et al., 2000; Trunova., 2012).

Scientists from Belarus investigated the influence of six test LED-based light sources with various spectral compositions, modeling optical radiation close to solar light, on the photochemical activity of leaves of basil. Based on the indicators of the initial photosynthetic process stages, the evidence attests to the essential possibility of modeling lighting conditions for plants in protected environments (Kabachevskaya et al., 2023). Furthermore, the spectral bandwidth of LEDs is narrow enough to generate lighting systems with optimal spectral distributions for different plant species and to control the photon flux density and exposure period within each spectral range independently. The creation and utilization of specialized light sources with a narrow spectral composition and intensity and duration that is adapted to the requirements of greenhouse tomatoes can not only boost yield but also enhance the quality of the end product (Turbekova, 2020). Tomatoes in the Akmola region are mostly grown under prolonged light conditions in winter greenhouses, where natural light is usually lacking during the winter period. The potential for growing tomatoes in protected conditions all year round requires a constant search for new methods of supplemental lighting at all stages of the tomato plant's vegetative period (Palmitessa et al., 2021).

In recent years, numerous experiments have been conducted by researchers worldwide. Although the results have been somewhat contradictory, all studies agree that tomatoes require a combination of red (R) and blue (B) spectral light (Zhang et al., 2018). Molchan et al. (2023) showed the benefits of applying FLORA LED light-emitting devices compared to HPS lamps (HPS 1000) for the cultivation of tall tomato varieties in production conditions. It is supposed that the increased photosynthetic activity and accelerated growth and development processes gave the LED plants greater adaptive potential and transplant survival. Earlier fruiting and higher yields (Molchan et al., 2023).

It is widely known that blue (B) and red (R) LED light combinations enhance the overall dry matter content, the density of photosynthetic pigments, and provide a good distribution of photosynthesis in tomato seedlings (Javanmardi & Emami, 2013; Gomez & Mitchell, 2015; Ouzounis et al., 2015; Matsuda et al., 2016; Wei et al., 2017; Izzo et al., 2020; Garcia & Lopez, 2020). Concurrently, Lanoue et al. (2018) highlighted that the connection between transpiration and carbon export can be more complicated than what has been presumed. They maintained that orange and green LEDs, not only the conventionally used red and blue LEDs, should be taken into account and experimented on in the design of lighting systems for the optimization of leaf performance in the cultivation of tomatoes in controlled environment systems (Lanoue et al., 2018). For this research, experimental greenhouse LED units KSDO1 and KSDO2 were used, which were domestically produced and designed for hydroponic systems. The LED fixtures tested had advanced semiconductor-based spectral LEDs as the basic source of light with proprietary spectral tuning technology developed by the Kazakh company "LedSystemMedia." The company has the equipment needed to manufacture LED light devices for industrial use and has several patents in the area of LED lighting technology, including for the tested fixtures (Taukenov et al., 2019; Meiramkulova et al., 2021). The primary objective of this research was to evaluate the performance of two locally developed LED lighting systems (KSDO-1 and KSDO-2) compared with conventional high-pressure sodium (HPS) lamps in greenhouse tomato production under hydroponic conditions. Specifically, the study aimed to determine the influence of LED illumination on plant growth and physiological responses, such as plant height, internode length, and leaf area, and the quantum yield of photosystem II (ΦPSII). In addition, the research sought to assess the effects of different lighting regimes on tomato yield and fruit characteristics, including fruit number, average fruit weight, marketable yield, and biochemical composition. The further objective was to examine the potential of domestically produced LED fixtures as energy-efficient alternatives to traditional lighting sources, thereby contributing to the development of sustainable and cost-effective greenhouse tomato production systems in Northern Kazakhstan.

MATERIALS & METHODS

The subject of research was the F1 Forticia RC tomato variety cultivated in the greenhouse complex conditions of "LedSystemMedia" LLP in Astana with the use of LED irradiators (LEDs) and high-pressure sodium lamps (HPS. control) on an experimental plot (Table 1; Fig. 1 and 2). The trials employed prototype greenhouse LED fixtures for supplemental lighting of tomato plants named KSDO1 and KSDO2. Which were domestically manufactured (hereinafter "fixtures"). They were intended to be sources of photosynthetically active radiation (PAR) for the growth of tomato crops. The fixtures employed energy-saving. High-efficiency LEDs combined with a proprietary local technology for creating an optimized light spectrum for tomato plant supplemental lighting (Taukenov et al., 2019). The trial location for tomato growth comprised LED irradiation systems, substrate, and a system for delivering nutrients. The irradiation systems provided adjustment of brightness within the range of 50–100%. Every LED light system possessed its unique spectral composition for every treatment group. Illumination intensity at 45 cm from the working surface was not below 200 μmol/(s·m²) over the whole area. Both the LED and conventional HPS lighting systems were used automatically. The photo period was 17 hours. Tomato growing was conducted according to the standard production technology of the "LedSystemMedia" LLP greenhouse complex (Meiramkulova et al., 2021). The development, production, and installation of the LED devices for tomato lighting were performed in line with the following methodological standards: State Standard of the Russian Federation: System of Product Development and Production Implementation Industrial and Technical Products. Procedure for Development and Production Implementation (GOST R 15.201-2000); and National Standard of the Russian Federation: Irradiation Devices with LED Light Sources for Greenhouses. General Technical Requirements (GOST R 57671-2017) (GOST R 15.201–2000; GOST R 57671–2017).

Table 1: Lighting Options for Tomato Plants

No.	Experimental Variant	Lamp Type	Photosynthetic Photon Flux Density (PPFD). μmol/s·m²	Spectral Ratio B:G: R:FR*. by PPFD. %
1	KSDO 1	KSDO-1	100–240	**
2	KSDO 2	KSDO-2	120–480	**
3	HPS (Control)	HPS	105–300	**

Note: Conditional division of the spectrum: B – blue; G – green; R – red; FR – far-red. Data is the intellectual property of LLP "LedSystemMedia"

Fig. 1: General view of the greenhouse complex of LedSystemMedia LLP. Astana. 2024.

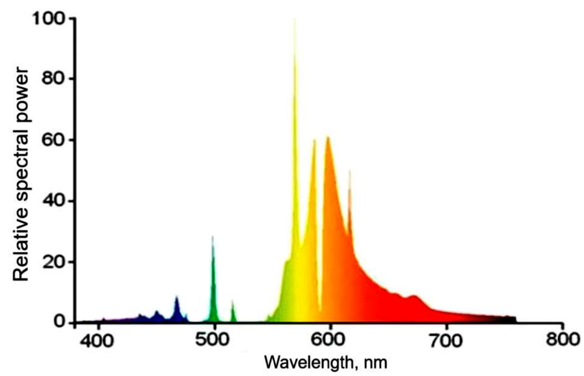

Fig. 2: Spectral power distribution of HPS (High-Pressure Sodium) lamp DNaT 600.

Experimental Setup and Phenological/Biometric Measurements

The trial was arranged in a randomized complete block design (RCBD) with three lighting treatments and four replications. Each replication consisted of an accounting plot of 2 m², with plants arranged in uniform density to ensure equal light distribution. Randomization of treatments was performed to minimize environmental and positional bias within the greenhouse compartments. The experimental design was based on the methodology of Dospekhov and the methodological guidelines for conducting experiments with vegetable crops in protected cultivation facilities (Vashchenko et al., 1976; Dospekhov, 1985). The accounting plot size was 2 m² with four replicates of each treatment in a randomized design. Biometric and phenological observations during the period of tomato cultivation were conducted according to the Official Method of State Variety Testing of Agricultural Crops (Gossort, 2019). Phenological stages noted were:

sowing date; individual and mass germination date; transplanting; flowering commencement and peak; position of the first inflorescence; planting to final position; and first and final fruit harvest dates.

Harvesting and Yield Assessment

Tomatoes were harvested at the stage of breaker or pink ripeness, occasionally at full ripeness. Yield was calculated using the formula:

$U = u + v \times n / 2.$

where:

U – total yield per plot normalized to the full number of plants.

u – observed plot yield.

v – observed yield per plant.

n – total number of plants per plot.

Assessment of Photosynthetic Productivity

Photosynthesis is the primary physiological process determining plant growth and development. Over 95% of plant dry matter is formed through this process. Photosynthesis management is regarded as the most promising method of affecting productivity and yield (Chakchir & Alekseeva, 2002; Bakharev et al., 2010; Zhantasov et al., 2011; Shchepetkov, 2013; Kuryanova & Oolonina, 2017). The photosynthetic performance of tomato leaves was measured with a small pulse fluorometer WALZ MINI-PAM-II (HEINZ WALZ GmbH. Germany). The instrument enables precise measurements of gas exchange both in the laboratory and in the field without any damage to the sample.

Evaluation of Biochemical Composition and Taste Quality

The biochemical tests of tomato fruit quality comprised dry matter content, total sugar, total acidity, ascorbic acid, carotene, and nitrates. The following methods were used in the biochemical tests: drying to determine dry matter, vitamin C and carotene by the Murray method, sugars by the Bertrand method total acidity by titration using 0.1N alkali solution, and nitrates by the Griess method. All original experimental records were kept following the methodological guidelines for vegetable experiments in protected structures (Vashchenko et al., 1976; Dospekhov, 1985; Litvinov, 2011).

Statistical Data Analysis

Standard methods of variation statistics were used to ensure the reliability of the experimental data (Prikupec, 2017). Microsoft Excel software (Office 2010 package) was used for statistical processing with a confidence level of 0.95. Data were presented as the arithmetic $\bar{x}$±SE of the mean (Sx). Differences between treatment means were considered significant at $P \leq 0.05$.

Agrotechnical Procedures

Seeds of the F1 hybrid 'Forticia RC' were sown on August 9, 2024 in mineral-wool starter trays. Germinated trays were maintained in a nursery unit under a uniformly controlled microclimate. At 15 days after sowing (seedlings 7–8cm tall, 2–3 true leaves), plants were transplanted into mineral-wool cubes. Eighteen days after transplanting, seedlings were arranged at a density of 25 plants m^{-2} to maximize light interception (Fig. 3). All plants were given the same irrigation and fertilization treatment. Electrical conductivity (EC) of the nutrient solution was kept at 1.3–1.7mS/cm. Tomato seedlings in the nutrient cubes were transplanted to their final growing positions under the LED lighting fixtures of two types, KSDO1and KSDO2, and under HPS lamps (control) on the 35th day after emergence (Fig. 4). Greenhouse air temperature was maintained at 20–22°C and relative humidity at 60–70%. Tomato cultivation followed the standard production technology adopted at LedSystemMedia LLP, Astana (Ramazanov, 2019).

Fig. 3: Tomato seedlings (F1 Forticia RC). 2024.

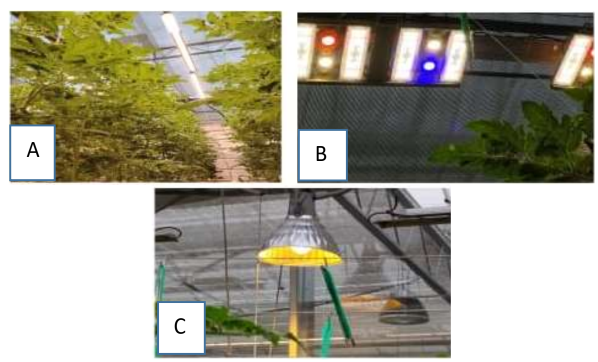

Fig. 4: Types of lamps used in the experiment: a – KSDO 1. b – KSDO 2. c – HPS (control).

RESULTS AND DISCUSSION

The hybrid tomato F1 Forticia RC under study showed vigorous growth and quick biomass accumulation irrespective of light conditions, with a stem height of 2 meters or higher 45 days after transplanting to the permanent location (Table 2). The first fruiting (first fruit picking) was noted on 19 November 2024, which was the 98th day of growth, revealed that this hybrid is early-maturing (Fig. 5). The stem height graph drawn according to data observed during the vegetation season indicates that stem growth under all types of lighting went on uniformly without delays in growth development and amounted to more than 6 meters during the seventh month of the growing season (Fig. 6). About leaf area, there was a notable difference among lighting treatments. During the early vegetative stage, the plants grown under control HPS lighting had a greater leaf area, 8205.3cm^2, than those grown under KSDO-1 (6320.5cm^2) and KSDO-2 (6600.1cm^2). Nevertheless, as plant growth developed, the plants grown under the LED systems studied had 20–24% greater leaf areas compared with the control (Table 3). This tendency remained constant during the entire cultivation cycle. Quantum yield measurements of Y(II) of photosystem II of F1 Forticia RC tomato leaves also revealed greater values under the KSDO-1 and KSDO-2 LED lights than under the HPS control (Table 4).

Table 2: Stem Height of F1 Forticia RC Tomato under Different Lighting Conditions. Cm

No.	Date of Measurement	HPS (Control)	KSDO-1	KSDO-2
1	20.09.24	52.2	53.0	53.7
2	04.10.24	100.7	98.5	99.5
3	18.10.24	154.3	142.6	139.3
4	01.11.24	194.7	183.5	182.9
5	15.11.24	227.1	216.3	211.7
6	29.11.24	252.4	242.7	244.7
7	13.12.24	322.7	303.7	304.3
8	27.12.24	364.3	347.9	354.2
9	10.01.25	411.1	395.3	393.4
10	24.01.25	457.8	435.5	440.7
11	07.02.25	500.5	486.7	487.0
12	21.02.25	541.5	533.8	533.3
13	07.03.25	584.9	579.9	580.0
14	14.03.25	606.5	601.7	601.7

Table 3: Leaf Area of F1 Forticia RC Tomato. cm^2

No.	Measured Leaf	Date	HPS (Control)	KSDO-1	KSDO-2
1	3rd leaf	20.09.24	8205.3	6320.5	6600.1
2	8th leaf	04.10.24	8858.9	11055.1	10833.1
3	12th leaf	18.10.24	7342.4	10310.5	9861.7
4	18th leaf	01.11.24	12630.7	14166.7	14094.7
5	27th leaf	22.11.24	10495.7	11577.1	11599.9
6	38th leaf	20.12.24	9959.0	11766.5	11742.8
7	44th leaf	03.01.25	8452.7	10019.1	10190.5
8	52nd leaf	24.01.25	8574.1	8245.9	7882.8
9	58th leaf	07.02.25	8342.6	9598.6	9273.9
10	61st leaf	21.02.25	8039.7	9185.1	9285.6
11	74th leaf	14.03.25	7947.4	9704.7	10814.1

Table 4: Y(II) Quantum Yield of Photosynthesis in Tomato Leaves

№	Date	HPS (Control)	KSDO-1	KSDO-2
1	20.09.24	0.457	0.410	0.433
2	27.09.24	0.306	0.449	0.475
3	04.10.24	0.557	0.525	0.488
4	11.10.24	0.543	0.429	0.453
5	18.10.24	0.511	0.436	0.456
6	25.10.24	0.460	0.611	0.535
7	01.11.24	0.413	0.450	0.487
8	08.11.24	0.416	0.419	0.460
9	15.11.24	0.377	0.450	0.456
10	22.11.24	0.416	0.415	0.457
11	29.11.24	0.421	0.497	0.433
12	13.12.24	0.512	0.530	0.538
13	20.12.24	0.457	0.602	0.556
14	27.12.24	0.426	0.470	0.448
15	03.12.25	0.463	0.461	0.472
16	10.01.25	0.438	0.479	0.450
17	17.01.25	0.427	0.473	0.466
18	24.01.25	0.420	0.390	0.423
19	07.02.25	0.421	0.439	0.444
20	14.02.25	0.457	0.469	0.460
21	28.02.25	0.525	0.532	0.474
22	14.03.25	0.449	0.464	0.486
23	31.04.25	0.435	0.483	0.521

Fig. 5: Tomato plants F1 Forticia RC. 2024.

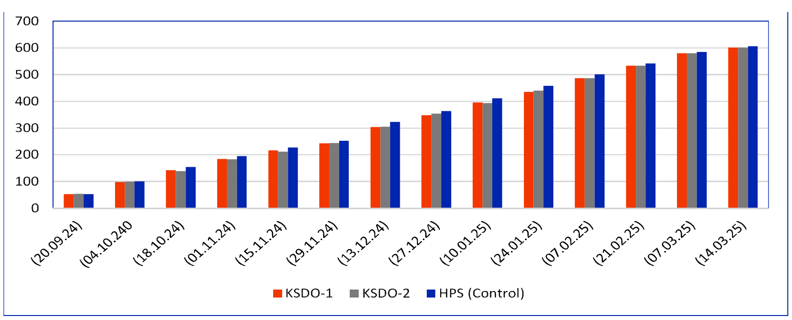

Fig. 6: Stem height of F1 Forticia RC tomato under different lighting conditions.

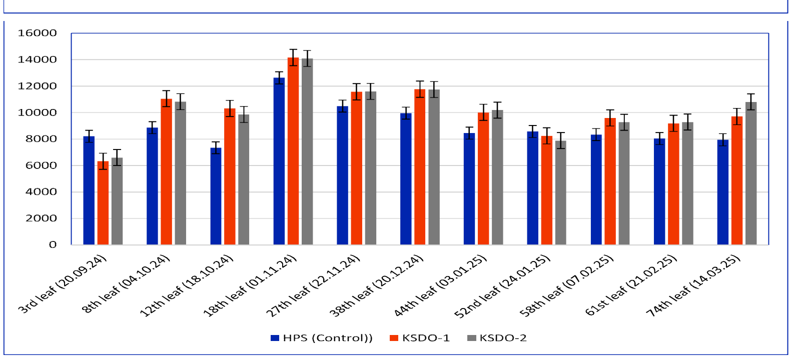

Fig. 7: Leaf area (cm^3) of F1 Forticia RC tomato (monthly measurements).

Quantum yield is the ratio of CO_2 molecules assimilated or O_2 molecules released to the number of quanta absorbed by the photosynthetic machinery (Fig. 7).

Tomato yield is determined by several factors, most notably, average fruit weight, number of fruits per plant, and in protected cropping systems, where vertical space is being used, by the number of inflorescences produced per unit plant height. Indeterminate tomato cultivars and hybrids are widely cultivated in greenhouses, developing flower clusters at each third leaf. A key factor for productivity is the length of internodes; the shorter the internodes, the more clusters are developed on the same stem height. Internode lengths were also measured in our research as a reflection of the potential for increased flower cluster density and thus higher yield (Table 5). At similar plant heights tomatoes under KSDO-1 and KSDO-2 lighting had shorter internodes than those under HPS lighting (Fig. 8). Tomato plant yield under the KSDO-1 and KSDO-2 LED treatments was 150.19% and 152.65% respectively, more than the control (HPS light) (Table 6). Average fruit weight was also greater under these treatments than in the control. Marketable fruit yield analysis indicated a higher number of fruits per plant in KSDO-1 and KSDO-2 conditions, 152.6 and 137.9 fruits, respectively, than in the control with 129.1 (Table 7). The yield dynamics chart showed high early yield production in the first fruiting month in all three light treatments, attesting to the early maturity of the F1 Forticia RC hybrid (Fig. 9). Moreover, the experimental lighting systems KSDO-1 and KSDO-2 provided prolonged fruiting until the end of February (Fig. 10). There were no notable differences in biochemical composition among treatments (Table 8). This study demonstrated that locally engineered LED fixtures (KSDO-1 and KSDO-2) substantially enhanced canopy development and yield of greenhouse tomato (F1 Forticia RC) compared with HPS lamps without compromising fruit biochemical quality. Across the production cycle, LEDs increased leaf area by ~20–24% relative to HPS and shortened internodes, while ΦPSII (PSII quantum yield) was consistently higher under both LED treatments. These responses culminated in markedly greater marketable productivity (≈150–153% vs HPS). The absolute magnitude of yield gains depends on the cultivar, environment, and light-management strategy; however, the direction of the effects is consistent with current knowledge of how spectral quality and photon delivery influence tomato morphogenesis, photosynthesis, and source–sink dynamics.

Table 5: Internode Length of F1 Forticia RC Tomato. cm

No.	Measured Leaves	Date	HPS (Control)	KSDO-1	KSDO-2
1	3rd–4th leaves	20.09.24	6.2	5.43	5.7
2	11th–12th	25.10.24	12.1	10.7	12.3
3	24th–25th	22.11.24	9.8	8.8	11.1
4	34th–36th	20.12.24	10.0	9.8	9.5
5	48th–50th	24.01.25	9.8	9.2	8.8
6	58th–60th	21.02.25	8.4	8.3	7.6
7	70th–72nd	14.03.25	10.0	8.5	8.2

Table 6: Productivity of F1 Forticia RC Tomato (Extended Cycle. Oct 2024 – Feb 2025)

Variant	Yield per replicate. kg/m²	Avg. Yield	Increase over Control. %	Avg. Fruit Weight. g
	1	2	3	
HPS (control)	8.045	8.618	9.317	8.659
KSDO-1	11.533	14.258	13.226	13.005
KSDO-2	14.231	14.892	10.533	13.218

Table 7: Total Number of Fruits of F1 Forticia RC Tomato by Lighting Option

Variant	Replicates (Total Fruits)			Average
	1	2	3	
HPS (control)	110	130	147	129.1
KSDO-1	119	157	138	137.9
KSDO-2	154	172	132	152.6

Table 8: Total Number of Fruits of F1 Forticia RC Tomato by Lighting Option

Variant	Dry Matter. %	Vitamin C. mg/%	Total Sugars. %	Titratable Acidity. %	Carotene. mg/100g	Chlorophyll a	Chlorophyll b
HPS (control)	5.17	19.36	2.625	0.6125	2.79	2.61	0.9375
KSDO-1	5.185	18.57	3.125	0.6175	2.325	2.9175	1.135
KSDO-2	5.17	20.785	2.7975	0.6525	2.1	2.68	1.11

A core mechanism underpinning these gains is spectral alignment with tomato photobiology. Red photons (600–700nm) are highly photosynthetically efficient and strongly drive carbon assimilation, whereas blue photons (≈450nm) regulate photomorphogenesis producing shorter sturdier plants with thicker leaves and higher pigment density traits that generally improve light use deeper in the canopy. Izzo et al. (2020) showed that removing both red or blue disrupted early tomato development and photosynthetic traits confirming the

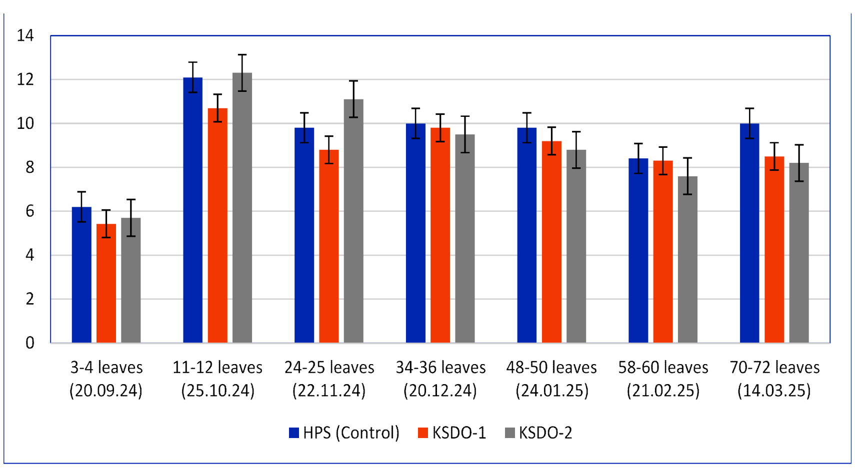

Fig. 8: Internode length of F1 Forticia RC tomato under different lighting conditions.

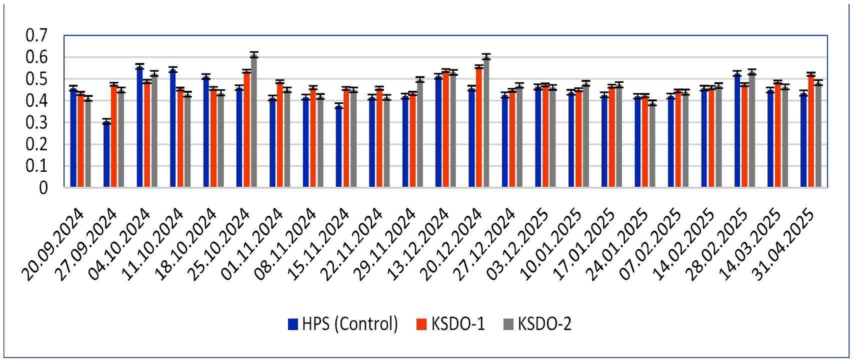

Fig. 9: Y(II) quantum yield of photosynthesis in leaves of F1 Forticia RC tomato.

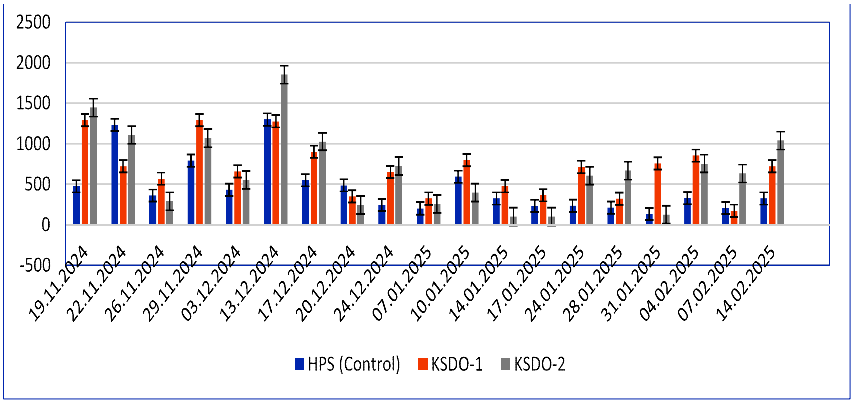

Fig. 10: Yield of F1 Forticia RC tomato. g/plot.

need for both bands during the seedling and early vegetative phases. Our LED treatments combined substantial red with moderate blue which is consistent with studies reporting higher chlorophyll content improved photosynthetic efficiency and enhanced vegetative growth under red-blue mixes. For example, Li et al. (2021) found that mixed red-blue light promoted photosynthetic efficiency and carbon assimilation in tomato seedlings relative to single-band treatments.

The observed internode shortening under LEDs aligns with prior work: blue light suppresses excessive stem elongation via cryptochrome- and phototropin-mediated signaling, thereby concentrating reproductive nodes per unit stem length—an architectural shift that can increase cluster density and ultimately yield in indeterminate tomatoes. Izzo et al. (2020) reported a more compact morphology when blue was present, while broader syntheses indicate that red-blue mixtures optimize both form and function in tomato compared with monochromatic spectra. Our data show that KSDO-1 and KSDO-2 reduced internode length relative to HPS; this likely increased inflorescence density along a given stem height and contributed to the higher fruit count per plant. The role of far-red (FR) is more nuanced. FR can promote elongation and leaf expansion through phytochrome signaling, potentially improving light interception in young canopies; however, excessive FR may shade-acclimate the plant and divert resources to elongation at the expense of compactness. A mechanistic perspective by Lanoue et al. (2018) highlighted that spectral quality modulates stomatal conductance and transpiration independently of carbon export rates in tomato leaves, implying that canopy-level outcomes depend on how spectra tune both gas exchange and energy balance rather than on photosynthesis alone. Our fixtures delivered modest FR relative to red and blue (manufacturer-tuned), which may have supported early leaf expansion without triggering undesirable elongation consistent with the combination of larger leaf area, shorter internodes, and a higher ΦPSII we recorded.

Beyond morphology and leaf-level efficiency, spectral quality influences transplant vigor and early canopy establishment stages that set the trajectory for yield. Garcia and Lopez (2020) demonstrated that supplemental radiation quality during propagation changes transplant architecture and biomass in tomato (and other solanaceous crops), with red-blue and red–blue–green mixes shaping stem diameter, leaf area, and dry mass. Although our study focused on production plants rather than transplant nurseries, the early vegetative advantages we observed under LEDs likely compounded over time, improving cluster initiation and fruit set. Reviews specific to tomato further emphasize that optimal spectra and photoperiod management should be latitude- and season-aware, especially under high-latitude winters, so that photon delivery complements limited daylight while controlling operating costs. Palmitessa et al. (2021) synthesized these management principles and argued that LED supplemental lighting can be tailored to climate and daily light integral often at lower installed power than legacy systems in certain regions. Energy efficiency and heat management also help explain performance differences between LEDs and HPS. While precise fixture efficacies vary by model and era, modern top light analyses report HPS photon efficiencies around ~1.7–2.1 μmol J^{-1}, whereas contemporary horticultural LEDs frequently surpass this and crucially allow spectral targeting that HPS cannot provide. Verheul et al. (2022) noted these benchmarks for HPS and discussed scenarios in which artificial top light strategies improved production efficiency. Earlier comparative work by Nelson and Bugbee (2014) showed that although initial LED capital costs were historically higher, spectral control and improving LED efficacies narrowed or reversed lifecycle cost differences, particularly where electricity is expensive or heat loads from HPS are undesirable. In our experiments reduced heat from LEDs likely improved microclimate uniformity near the canopy, minimizing overheating hotspots typical of HPS and supporting sustained reproductive performance late into the cycle. Coupled with the higher ΦPSII under LEDs these physical and physiological advantages plausibly underlie the extended fruiting window we observed. Importantly, our LED treatments did not alter fruit biochemical composition relative to HPS. This is consistent with studies showing that when nutrients and climate are controlled, spectral shifts that improve canopy light distribution and photosynthesis need not trade off with fruit quality.

Recent syntheses on red–blue LEDs in tomato report increased leaf chlorophylls and carotenoids and tighter regulation of vegetative growth, with no consistent detriments to fruit-quality metrics; when effects occur, they tend to be cultivar-specific and dose-dependent. Accordingly, the unchanged biochemical profiles in our fruit despite higher yields suggest that LED-driven gains were achieved primarily through improved canopy architecture and photosynthetic performance rather than quality compromises (Nelson and Bugbee 2014). Our findings also align with the practical lens emphasized by Palmitessa et al. (2021) namely, that LED deployment should be matched to local constraints (latitude, electricity costs, greenhouse design) and crop stage. In this context, KSDO-2 was the best performer, indicating that a domestically engineered, crop-tuned spectrum can deliver agronomic benefits during Northern Kazakhstan's low-light season.

Where long photoperiods and cool outdoor conditions elevate the importance of efficient photons and controllable heat loads. The strong yield response, along with stable fruit chemistry, positions KSDO-2 as a candidate for broader commercial rollout particularly in facilities seeking to reduce energy intensity without sacrificing throughput. Two caveats merit discussion. First, our ANOVA confirmed significant treatment effects on yield morphology and ΦPSII the large yield increase relative to HPS likely reflects the combined influence of the spectrum, photon flux density, and photoperiod control. Literature showed that the benefits from LEDs range widely depending on the fixture's efficacy spectrum. Outcomes also vary with DLI targets and cultural practices, with some studies reporting only modest gains, while others observe substantial improvements when legacy lighting systems are poorly aligned with crop requirements. Second, we evaluated only one hybrid under a single greenhouse regime; yet cultivar-by-spectrum interactions can be substantial, and differences in irrigation or CO_2 set-points across spectra may shift whole-plant water-use efficiency—consistent with reports of altered canopy-level transpiration under LED versus HPS lighting. Future research should therefore (i) compare multiple cultivars (ii) evaluate cost–benefit across seasons and (iii) integrate CO_2 enrichment and climate control strategies tailored to specific spectra to optimize both yield and resource intensity (Arif et al., 2024). In summary, aligning supplemental lighting spectra with tomato photobiology requires a sample red for photosynthesis sufficient blue to constrain elongation and improve leaf traits and carefully dosed FR produced a compact productive canopy with higher ΦPSII and prolonged fruiting. These outcomes agree with controlled environment evidence that mixed red–blue (with optional green/FR contributions) enhances transplant quality canopy photosynthesis and yield potential relative to HPS, particularly in high-latitude or low-DLI contexts. Given the sizable performance gains observed and the regional need for energy-savvy winter production, the KSDO-2 fixture appears especially promising for commercial adoption in Northern Kazakhstan.

Conclusion

F1 hybrid tomato 'Forticia RC' exhibited vigorous biomass accumulation and robust growth across all lighting regimes, with first fruit set at day 98, confirming its early-maturing status. Leaf area differed notably among treatments: plants under KSDO-1 and KSDO-2 had 20–24% larger leaves than those under HPS. The effective quantum yield of PSII [Y(II)] was likewise higher under KSDO-1 and KSDO-2 than under HPS. Internodes were shorter with both LED treatments—shortest under KSDO-2—leading to greater inflorescence density and a potential yield advantage. Productivity under KSDO-1 and KSDO-2 exceeded the control by 150.19% and 152.65%, respectively. Overall, indices of biomass accumulation, fruit number, and total yield were highest with KSDO-2 compared with both HPS and KSDO-1. Based on these results, a utility-model patent application will be submitted for the KSDO-2 LED lighting device.

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